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REFERENCE

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American Journal of Science

JANUARY 1958

THE PETROLOGY OF A DIFFERENTIATED TESCHENITE SILL NEAR GUNNEDAH, NEW SOUTH WALES

J. F. G. WILKINSON

ABSTRACT. In ascending sequence, the Tertiary Black Jack sill, approximately 500 feet thick, consists of porphyritic and ophitic teschenites which grade into gabbro-type teschenites. Progressive decrease in olivine with increasing height above the lower contacts and increased amounts of clinopyroxene and iron ores in the upper intrusion levels constitute the principal modal variations. During differentiation the olivines become more fayalitic (Fa_{21} to Fa_{66}) while the plagioclase feldspar is enriched in albite (An_{72} to An_{49}). The associated bulk titaniferous clinopyroxene undergoes little compositional change with differentiation ($Ca_{46}Mg_{37}Fe_{18}$ to $Ca_{47}Mg_{36}Fe_{19}$). A widespread and characteristic feature of the teschenites is a microcrystalline alkaline mesostasis, approximating in its chemical composition to analcite syenite. Evidence is presented suggesting that the variations in the teschenites and their component minerals can be adequately explained by the mechanism of fractional crystallization. Gravitative movement of crystals is not believed to have been a significant factor in the evolution of the sill.

INTRODUCTION

The Black Jack teschenite sill, named from Black Jack Mountain (2,200 feet) which owes its existence to the rocks under discussion, is located four miles southwest of the township of Gunnedah on the northwestern slopes of the New England Tableland, approximately 200 miles north-northwest of Sydney (fig. 1). Coal has been mined from two seams in Permian sediments which underlie Black Jack Mountain. Differential erosion has revealed the sill as a near-horizontal circular mass, with an average diameter of one mile. The intrusion possesses a relatively flat top, bounded by rather steep sides with frequent extensive outcrops (pl. 1). The degree of preservation of the sill provides opportunity for the study of material whose location can be fixed in relation to the intrusion as a whole. As far as outcrops allowed, specimens were collected on lines radial to the center of the intrusion (sections A to D, face E), and traverses across the roof of the sill (traverses F to I) (fig. 2). In the sections up the face of the sill, specimens were collected from a vertical or near-vertical columnar outcrop, at least six to twelve feet in height. The specimens studied have been plotted on a contoured geological map of the intrusion (fig. 2). Table 2 contains details of the height in feet of the specimens above the lower intrusion contacts.

The present study has been primarily one of evaluating the progressive changes during the evolution of an intrusion of alkali olivine basalt type (Tilley, 1950). Accent has therefore been placed on the following themes: (1) modal and textural variation within the rock series; (2) compositional changes within the principal mineral series and the relations of these minerals to both the parent rocks and associated minerals; (3) major and minor element trends in the rocks and minerals; (4) a discussion of the generalized

Fig. 1. Outline map showing the distribution of alkaline basic sills and laccoliths in New South Wales and southeast Queensland. (1) near Ipswich and Beaudesert (Jensen, 1909; Benson, 1913); (2) west of Kyogle (Browne, 1927); (3) Nandewar Mountains (Jensen, 1907); (4) Gunnedah; (5) Liverpool Range, (6) Mt. Royal Range (Benson, 1911); (7) Muswellbrook-Singleton area (Raggatt and Whitworth, 1932); (8) Prospect, near Sydney (Jevons et al, 1911, 1912; Browne, 1924); (9) Southern Coalfield (Edwards, 1953); (10) near Bombala (Browne, 1927).

PLATE 1

The Black Jack sill from a point 1¼ miles east of the intrusion. The arrows A-D indicate the approximate locations of sections A-D. Face E is on the opposite side of Black Jack Mountain, in the area between sections B and D. Note the relatively flat top to the intrusion, and the terrace marking the junction between the teschenites and sediments of the Black Jack Formation.

cooling history of the intrusion and the differentiation mechanism (or mechanisms) responsible for any variation in (1) (2) and (3).

Aspects of (2) concerning the olivines, clinopyroxenes and titanomagnetities have already been discussed (Wilkinson, 1956b; 1957a; 1957b). The present paper deals primarily with (1) and (4), plus certain aspects of (2) and (3). Wherever possible, comparison has been made with certain features of tholeiitic rocks. It is proposed to deal with the minor elements of the teschenite rock and mineral series in a subsequent paper.

References to the Black Jack rocks have been made by Kenny (1928; 1929), Hanlon (1947; 1949), Walker and Poldervaart (1949, p. 688) and David (1950, p. 578). David (op. cit., p. 578-582) has summarized the role of alkali olivine basalt magma in Eastern Australia. At present, undersaturated basic alkaline intrusions (nepheline- or analcite-bearing) are known in an area extending from southeast Queensland to southeast New South Wales (fig. 1). The writer has also found intrusions of teschenite to be frequent field associates of lavas belonging to the New England Tertiary alkali olivine basalt province, particularly in the area between Armidale and Glen Innes.

TABLE 1

The Permian Sequence in the Gunnedah Area
(after Hanlon, 1947; 1949; D. Hill, 1955, fig. 5)

Permian units in the Gunnedah area	Approx. Thickness	Lithology	Permian sequence in the Hunter Valley, near Newcastle
Black Jack Formation	550 feet	sandstones, shales, conglomerates, cherts and minor bands of limestone; two coal seams	Newcastle and Tomago Coal Measures
Gladstone Formation	300	almost entirely shales with odd bands of conglomerate and carbonaceous matter	Maitland Group[1] — Mulbring Sub-Group
Porcupine Formation		sandstones with beds of conglomerate	Maitland Group[1] — Branxton Sub-Group (Artinskian-Kungurian)
Lower Coal Measures	200	shales with abundant Glossopteris	Greta Coal Measures
Boggabri Volcanics		acid to intermediate lavas and tuffs; amygdaloidal basalts	Dalwood Group[2]

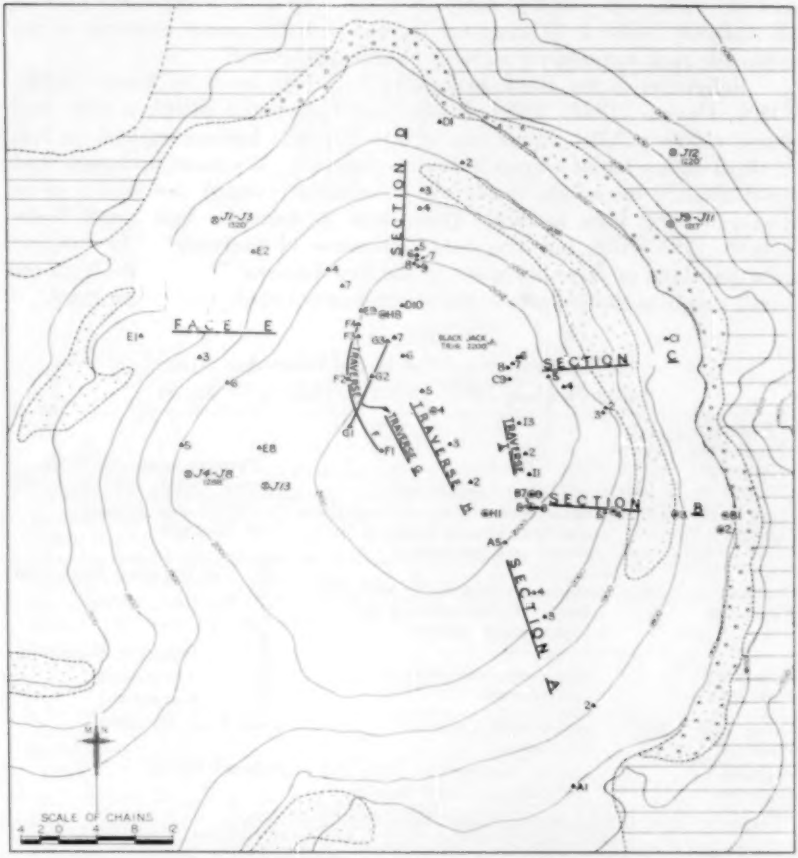
[1] Formerly Upper Marine Series (David, 1950, p. 340).

[2] Formerly Lower Marine Series (David, op.cit., p. 338).

GENERAL GEOLOGY OF THE INTRUSION

The general geology of the Gunnedah area has been discussed by Hanlon (1947; 1949, especially pl. XVI). The main units are Permian, Triassic and Tertiary. Regional dips of the Permian and Triassic are generally of the order of 5° to 10° in a general southwesterly direction, with broad shallow flexures superimposed over the regional dips. The Permian sequence has been summarized in table 1, together with correlations with the type Hunter Valley sequence (after D. Hill, 1955). Of the Permian units, only the Black Jack Formation is developed in the vicinity of the sill (fig. 2). The lateral per-

sistence of marker horizons (chert bands and coal seams) in the Black Jack Formation indicates the absence of powerful deformation accompanying the intrusion of the basic rocks. However zones of minor disturbance occur within the colliery workings. Thus two northeast-trending tensional faults occur in the vicinity of the northwest and southeast teschenite contacts in figure 2. The



LEGEND

TERTIARY — TESCHENITE

TRIASSIC — SANDSTONE

TRIASSIC — CONGLOMERATE

PERMIAN — BLACK JACK FORMATION: SANDSTONES, SHALES, CONGLOMERATES, CHERTS & COAL SEAMS

A4▲ SPECIMEN LOCATIONS

H7● ANALYSED SPECIMENS

●1217' LOCATIONS OF FEEDER DYKE SPECIMENS

1700 SURFACE CONTOURS

Fig. 2. Geological map of the Black Jack sill.

Triassic sediments lying above the Black Jack Formation vary in thickness from 80 to 100 feet. At a height of approximately 1,700 feet, the lower teschenite contacts are encountered. Unfortunately both thick scree cover and differential erosion gullies in the vicinity of the contacts have so far prevented the discovery of chilled teschenite selvages.

As now revealed, the generally concordant Black Jack intrusion possesses an average thickness of approximately 500 feet, and appears to dip at low angles to the southwest. Greater thicknesses of teschenite probably exist at King Jack (2470 feet), 3 miles to the southwest. Above the base of the Black Jack sill and occurring within it, are four "slabs" of Triassic sediments (dominantly thin-bedded friable sandstones). These rocks have not been tilted away from the regional dip.

PETROGRAPHY

Although the mineralogical constitution of the teschenites remains relatively constant, the principal variation exists in their grainsize and fabric, and in the habits and relative percentages of the component minerals. The latter variation is not sufficient to carry the rocks outside the teschenite group. The writer has previously discussed the varying meaning and emphasis of the terms "teschenite" and "crinanite" (Wilkinson, 1955).

As in the tholeiitic Skaergaard intrusion (Wager and Deer, 1939, p. 87), two generalizations greatly simplify the petrography of the various rock types, namely: (1) rocks of the same horizon are similar, except for occasional differences in relative abundance of the minerals; (2) the difference between average rocks of different horizons is a gradual one, being a function of the height of the rock in the intrusion. For petrographic purposes the Black Jack rocks can be most conveniently classified on a basis of textural differences, according to the three-fold scheme proposed by Walker (1923a; 1923b) for the Scottish teschenites.

(1) *Porphyritic or basalt type.*—Characterised by conspicuous phenocrysts of fresh olivine and titanaugite, frequently forming glomeroporphyritic aggregations. The grain is fine to medium (pl. 2-A; Walker, 1923b, pl. XI, fig. I).

(2) *Ophitic or doleritic type.*—Typically non-porphyritic and characterised by well-marked ophitic or sub-ophitic relationships between the titanaugite and plagioclase. The olivine is invariably serpentinized and the grain is medium to coarse (Walker, op. cit., fig. II; M. P. C. 41025[1]).

(3) *Non-ophitic or gabbro type.*—Typically non-porphyritic and characterized by even-grained hypidiomorphic texture. In the varieties rich in analcite, both the titanaugite (and barkevikite) are markedly euhedral. Ophitic structure is absent and the olivine invariably serpentinized. The grain is medium to coarse (pl. 2-C; Walker, op. cit., fig. III; M. P. C. 41062).

In a general way, these three divisions represent in order (1 to 3) the teschenite sequence with increasing height above the base of the Black Jack sill. Future work on similar Eastern Australia rock types may permit their

[1] Thin-section numbers in the Harker Collection, Dept. of Mineralogy and Petrology, Cambridge, England.

TABLE 2
Modal Composition, Specific Gravity and Plagioclase Compositions of Teschenites in Sections A to D, Face E
(Note: All modal values in volume percent)

Specimen number	Height in feet above lower contact	Olivine	Clino-pyroxene	Iron Ore	Feldspar
A1	40	17.9	22.5	7.4	39.9
A2	140	8.5	24.3	8.1	43.3
A3	340	6.7	22.4	7.7	40.0
A4	370	4.3	21.8	6.5	46.0
A5	440	4.5	21.2	6.3	37.8
B1	20	23.0	19.7	10.2	38.0
B2	20	19.1	21.8	11.5	28.7
B3	120	7.2	23.3	6.2	47.9
B4	270	15.0	23.0	7.8	40.4
B5	300	7.3	20.4	7.3	25.3
B6	400	10.3	19.3	6.5	50.1
B7	420	6.3	22.5	9.8	44.9
B8	460	1.6	25.6	14.7	17.3
B9	500	2.0	29.2	11.0	32.2
C1	60	10.4	20.0	9.8	43.7
C2	300	8.4	24.5	6.0	35.2
C3	315	8.2	22.5	8.6	47.9
C4	360	12.0	24.7	7.8	43.5
C5*	400	5.5	25.9	7.9	41.8
C6	440	4.2	20.5	8.7	45.9
C7*	460	1.8	27.0	10.9	25.0
C8*	465	1.2	27.4	12.5	15.2
C9*	480	1.0	26.6	9.9	12.5
D1	50	23.0	21.0	10.7	38.4
D2	80	13.2	20.5	11.3	37.5
D3	180	14.8	21.1	6.8	41.8
D4	220	14.9	21.4	7.1	36.2
D5	330	10.0	20.9	8.5	47.6
D6	365	5.5	20.0	9.6	46.9
D7	380	5.5	23.5	10.0	42.5
D8*	390	1.8	27.2	12.1	29.3
D9*	400	3.8	22.0	12.1	42.0
D10*	440	—	27.0	14.0	16.0
E1	90	17.6	22.0	6.7	37.6
E2	190	20.0	22.3	5.6	40.1
E3	210	9.4	19.0	6.5	52.2
E4	350	12.4	27.0	10.2	37.6
E5	350	4.3	26.7	9.0	40.0
E6	350	5.2	23.1	7.3	48.0
E7	390	7.7	23.0	7.8	49.5
E8	410	3.8	26.0	6.2	42.0
E9	450	5.9	20.8	8.8	48.6

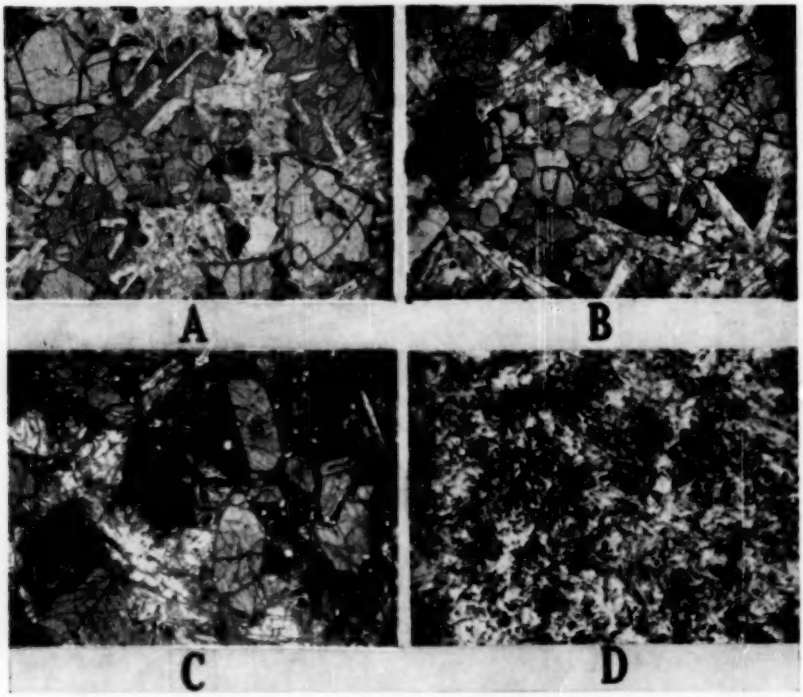
* Indicates gabbro-type teschenites.

TABLE 2 (Continued)

Zeolite and indeterminable mesostasis	Minerals additional to those in col. 3-7.	Specific gravity	Plagioclase composition (mol. percent)
12.3	—	2.93	An_{67}
15.8	—	2.86	An_{61}
23.2	—	2.85	An_{60}
21.4	—	2.83	An_{54} (An_{32}) †
30.2	—	2.83	An_{56}
9.1	—	2.95	An_{68}
18.9	—	2.91	An_{66}
15.4	—	2.83	An_{62} (An_{32})
13.8	—	2.86	An_{62}
39.7	—	2.78	An_{58}
13.8	—	2.84	An_{57}
16.5	—	2.84	An_{59}
33.0	Chlorite 7.8	2.93	An_{59} (An_{48})
25.6	—	2.90	An_{57}
16.1	—	2.86	An_{70}
25.9	—	2.85	An_{62}
12.8	—	2.81	An_{62}
12.0	—	2.90	An_{60}
18.9	—	2.85	An_{61}
20.7	—	2.84	An_{61} (An_{48})
35.3	—	2.88	An_{60} (An_{39})
43.7	—	2.90	An_{55}
39.1	Chlorite 8.0—Apatite 2.9	2.88	An_{54}
6.9	—	2.95	An_{62} (An_{51})
17.5	—	2.90	An_{61}
15.5	—	2.90	An_{59}
20.4	—	2.90	An_{62}
13.0	—	2.89	An_{60}
18.0	—	2.85	An_{62}
18.5	—	2.83	An_{60}
29.6	—	2.92	An_{59}
20.1	—	2.88	An_{59}
38.0	Apatite 5.0	2.88	An_{59}
16.1	—	2.92	An_{70}
12.0	—	2.96	An_{72}
12.9	—	2.84	An_{60}
12.8	—	2.91	An_{60}
20.0	—	2.85	An_{62}
16.4	—	2.85	An_{62}
12.0	—	2.87	An_{61}
22.0	—	2.82	An_{62}
15.9	—	2.85	An_{61}

† Values in brackets refer to composition of outer zones of plagioclase, determined by refractive indices.

PLATE 2



A. Teschenite (porphyritic type). The olivine phenocrysts which reveal a tendency towards idiomorphism, are indented by adjacent plagioclase, while the clinopyroxene in this field is dominantly ophitic. Most of the titanomagnetite is of early crystallization. Specimen B1, 20 feet above lower contact (table 6, anal. I). (Ordinary light x33).

B. Teschenite, illustrating glomeroporphyritic aggregation of olivine and clinopyroxene. This teschenite is dominantly ophitic in type. The titanomagnetite is now skeletal, and of late crystallization, being moulded around and interstitial to feldspar. Specimen E3, 350 feet above lower contact. (Ordinary light x33).

C. Teschenite (gabbro type). The clinopyroxene is idiomorphic while apatite is conspicuous. Considerable areas of iron-charged mesostasis are present in the upper right-hand portions of the photo. Specimen H8, height 2200 feet (table 6, anal. VIII). (Ordinary light x19).

D. Analcite syenite mesostasis, with alkali feldspar microlites (occasionally revealing slight curvature), pyroxene droplets and iron ore. The base is highly analcite and may contain interstitial carbonate. Specimen H4, height 2200 feet (table 6, anal. IX). (Ordinary light x33).
x33).

over-all classification along similar lines. In the Black Jack sill, the distribution of the gabbro-teschenites, generally at heights of 425 to 500 feet about the lower contacts, and their persistence in outcrop on the roof of the intrusion suggest that they represent a relatively well-defined upper horizon. However in some instances, junctions between ophitic and gabbro-teschenites in a single specimen point to their existance as coarse-grained schlieren (the

"pegmatitic teschenites" of Walker, 1930, p. 370; M. P. C. 28564), injected while the ophitic types were still in a plastic condition during the final stages of cooling. Mineralogically the gabbro-teschenites are distinguished from the lower rocks by their coarser grainsize, idiomorphic clinopyroxene, and the more extensive analcitization of the feldspars, the latter feature resulting from a higher concentration of zeolite and alkaline mesostasis.

The modes (volume percent) of the teschenites are given in tables 2 and 3; table 4 contains details of the average grain size of the principal mineral series in the analyzed teschenites (table 6).

Variation in the texture and habit of the *olivines* has already been discussed (Wilkinson, 1956b). In the basaltic and doleritic teschenites, the mauve *clinopyroxene* (a titaniferous salite) generally builds ophitic or sub-ophitic plates averaging 1.7 by 0.7 mm. In the gabbro-teschenites, the clinopyroxene occurs as idiomorphic columnar crystals up to 2 cms long, and with no visible curvature (cf. Benson, 1944, p. 97). Elongation is parallel to *c*. Elongation of the clinopyroxene is common in tholeiitic dolerite pegmatites (Walker, 1953, p. 44) and in the upper levels of certain tholeiitic sills e.g. the Hangnest sill, South Africa (Walker and Peldervaart, 1941, p. 443). Glomeroporphyritic aggregates of clinopyroxene are more common in the lower and middle teschenites (pl. 2-B). Where the clinopyroxene occurs in two generations, the smaller crystals, occasionally slightly skeletal, are confined to areas of mesostasis. In some of the gabbro-teschenites, the clinopyroxene occurs in myrmekite-like intergrowth with plagioclase (cf. Browne, 1927, p. 375; Lehmann, 1930, p. 337); elsewhere in similar rocks it may occur as several isolated but nevertheless optically continuous hook-like individuals (0.2 by 0.2 mm) in the zeolitic mesostasis. Extreme intricate skeletal outlines in some of the upper clinopyroxenes recall the "harpoon type" of skeletal augite described by Gansser (1950, p. 231). Where the clinopyroxene abuts against areas of analcite, it develops a minor mantle of green pyroxene (aegirine-augite or aegirine), a frequent mineralogical change in teschenites. Individual crystals of aegirine-augite or aegirine (0.2 by 0.2 mm) may be present in the mesostasis. Save for occasional minor development of calcite along cleavages, the clinopyroxene remains unaltered, despite often extensive alteration of the associated olivine, plagioclase or iron ore.

Phenocrysts of *plagioclase* (1.5 by 0.2 mm) are rare in the lower basaltic teschenites and the most widespread individuals, laths elongated parallel to (010), average 0.7 by 0.1 mm. A third generation of smaller laths is usually present in the groundmass (table 4). In the gabbro-teschenites, the plagioclase, dominantly of one generation, forms thick idiomorphic tabulae (3.0 by 0.8 mm), frequently with a mantle of *anorthoclase*. This latter mineral (frequently kaolinised) occurs also as single crystals, occasionally showing Carlsbad twinning. The plagioclase is probably the most susceptible of the principal mineral series to alteration. Analcitization is universal, and all changes may be traced from initial replacement to complete pseudomorphs of analcite. Replacement or alteration to sericite, kaolin, natrolite or thomsonite

TABLE 3

Modal Composition and Plagioclase Compositions of Teschenites from Traverses F to I

Specimen number	Barometer reading in feet	Olivine	Clino-pyroxene	Iron Ore	Feldspar	Zeolite, indeterminable mesostasis	Minerals additional to those in col. 3-7	Plagioclase composition (mol. percent)
F1	2140	3.4	21.1	11.4	43.7	20.4	—	An_{68}
F2	2090	3.2	21.0	9.6	40.2	26.0	—	An_{37} (An_{68}) **
F3*	2100	5.4	27.0	10.3	35.7	21.5	—	An_{68} (An_{48}) (An_{37})
F4*	2100	4.7	23.0	6.3	45.8	20.2	—	An_{65}
G1*	2160	4.6	22.0	14.0	24.0	35.4	—	An_{61}
G2	2140	4.1	22.1	9.7	40.7	23.4	—	An_{68}
G3*	2140	—	27.0	11.2	20.0	29.8	Chlorite 10.0 Apatite 2.0	An_{70} (An_{50})
H1*	2140	2.2	16.4	11.2	21.5	47.0	Sideritic carbonate 1.7	An_{70}
H2	2140	3.5	23.8	9.8	34.0	28.9	—	An_{68}
H3	2140	3.7	21.6	9.7	39.7	25.3	—	An_{61}
H4*	2200	—	17.7	9.4	30.6	36.9	Sideritic carbonate 5.4	An_{66}
H5*	2160	—	18.8	9.0	32.0	36.8	Apatite 3.4	An_{54}
H6	2140	6.1	19.7	6.2	48.8	19.2	—	An_{70}
H7*	2180	—	24.1	14.6	9.0	49.5	Apatite 2.8	An_{70}
H8*	2200	0.5	22.1	11.4	15.3	49.0	Apatite 1.7	An_{70}
11	2160	1.3	24.7	10.2	44.1	19.7	—	An_{68}
12	2180	6.4	26.4	9.0	47.8	10.4	—	An_{57}
13*	2180	—	23.6	14.7	22.5	36.6	Apatite 2.6	An_{54}

* Gabbro-type teschenite

** Values in brackets refer to compositions of outer zones of plagioclase, determined from refractive indices.

N.B. The mode for H4 is that of the teschenite in which the analysed microcrystalline vein mesostasis occurs.

TABLE 4

Dimensions of the Principal Mineral Series in the Analysed Teschenites
(All dimensions in mm)

Specimen number	Olivine		Pyroxene	Plagioclase			Iron Ore
	Phenocrysts	Groundmass	Average	Phenocrysts	Average	Microlites	Average
B1	1.6 by 0.7 (average)	0.3 by 0.3	1.7 by 1.2	1.5 by 0.2 (rare)	0.6 by 0.1	0.15 by 0.03	0.2 by 0.2
B2	1.3 by 0.5	0.3 " 0.3	2.0 " 1.5	1.5 by 0.15 (rare)	0.7 " 0.1	0.3 " 0.05	0.2 " 0.2
B3	0.7 " 0.4	0.3 " 0.3	1.5 " 0.7	3.0 by 0.3 (rare)	1.0 " 0.15	0.3 " 0.05	0.3 " 0.3
B4	1.5 " 0.7	0.3 " 0.3	1.2 " 0.4	1.5 by 0.2 (rare)	1.0 " 0.15	0.3 " 0.1	0.4 " 0.3
B7	0.7 " 0.5	0.3 " 0.3	1.5 " 1.4	2.0 by 0.25	1.2 " 0.2	0.4 " 0.1	0.6 " 0.6
B9*	ophitic olivines up to 3.0 by 3.0	rare	2.0 " 1.6	2.0 " 0.5	1.3 " 0.3	0.4 " 0.1	0.7 " 0.7
H1*	aggregates up to 6.0 mm in length	rare	3.0 " 2.0	3.2 " 1.7	1.6 " 0.3	rare	1.2 " 1.2
H8*	1.4 by 0.8 (rare)	—	3.0 " 2.0 although larger prismatic sections common	3 by 1.5		rare	1.5 " 1.5

* Gabbro-teschenites

is not common; albitization was not detected. Central plagioclase areas are frequently stained with migratory bowlingite or chlorite.

In the lower teschenites, *the iron ore* (a homogeneous titanomagnetite) is of early crystallization, occurring as cuboidal grains, frequently aggregated in the synneusis structure of Vogt. In the ophitic teschenites higher in the sill, the titanomagnetite grains, frequently with inclusions of feldspar and apatite, increase in size and become allotriomorphic (pl. 2-B). In the gabbro-teschenites, this mineral reveals a variety of intricate skeletal forms, most frequently as irregularly shaped reticulate crystals which in extreme cases resemble a kind of herring-bone structure (cf. Lehmann, 1930, figs. 9 to 12). Much of the ore in the gabbro-teschenites is concentrated in the mesostasis (pl. 2-C).

Analcite is always present, and exhibits three main modes of occurrence: (1) as a primary infilling, interstitial to the other minerals, and often carrying inclusions of apatite, biotite, iron ore and analcitized feldspar; (2) as a replacement mineral, distributed along cracks and cleavages of plagioclase and alkali feldspar; (3) as a filling of veinlets, which often traverse fractured crystals of earlier minerals (cf. Walker, 1930, p. 369), and in small vughs (1.5 to 2.0 mm in diameter) where it is often accompanied by other late-stage minerals. This latter mode of analcite occurrence is more characteristic of the gabbro-teschenites where the analcite, usually the first mineral deposited, presents idiomorphic faces to the other constituents. These include an *iron-rich chlorite*, with $\alpha = 1.638$ $\gamma = 1.665$ (± 0.003), pleochroism X = pale pinkish yellow, Z = green; *thomsonite*, with $\alpha = 1.529$ $\beta = 1.533$ $\gamma = 1.544$ (± 0.001); *natrolite*, with $\alpha = 1.484$ $\beta = 1.488$ $\gamma = 1.495$; iron ores; and a *ferruginous carbonate close to siderite*, with $\varepsilon = 1.595$, indicating 70 to 80 percent $FeCO_3$ (Winchell and Winchell, 1951, p. 109).

The *apatite* in the lower rocks most commonly forms needles and prisms (up to 1.5 by 0.03 mm) in the zeolite and mesostasis, but also occurs as inclusions in pyroxene, feldspar and olivine. The mineral increases in size (prisms up to 3.0 mm in length) in the gabbro-teschenites (pl. 2-C) and is then dominantly of late crystallization (cf. Tyrrell, 1928, p. 553, Flett, 1932, p. 152; Campbell, Day and Stenhouse, 1932, p. 352; Hutton, 1943, p. 359). Optical properties of nine grains occurring over the 500 foot thickness of the sill ($\varepsilon = 1.633$ to 1.634; $\omega = 1.636$ to 1.637) suggest the mineral is fluorapatite (Benson, 1945, appendix II, p. 314; Yagi, 1953, p. 789; Winchell and Winchell, 1951, p. 198). The apatite is unpigmented, but often contains a single central tube filled with mineral matter (hematite and analcite?), presumably due to trapping of late-stage liquids by continued growth of initially pronged skeletal apatites. Similar apatites have been described from the Lake Waihola theralite, New Zealand (Benson, 1942, p. 164).

Unchloritized *biotite*, never constituting greater than 1 percent of the mode, is a ubiquitous accessory, and occurs in two principal ways, namely as independent flakes (up to 0.3 by 0.3 mm) in the groundmass and mesostasis, or as flakes moulded on titanomagnetite. Rarely the biotite forms marginally to olivine or along cleavage traces of pyroxene or feldspar.

Particular attention is directed to varying amounts of *mesostasis* which occurs in rocks from all levels in the intrusion, generally as an infilling between pyroxene, feldspar and iron ore. In specimen H4, concentration of the mesostasis into crosscutting veinlets 2 cms in width has occurred (table 6, anal. IX). In thin section (pl. 2-D), the mesostasis consists of untwinned, partially kaolinised feldspar microlites (averaging 0.15 by 0.01 mm), droplets of titaniferous clinopyroxene and green alkaline pyroxene (sub-ophitic or intersertal to the feldspar), and dusty iron ore, all of which are set in a near-isotropic base, presumably highly analcitic. The feldspar is probably to be referred to a potassic alkaline type. In certain cases the mesostasis is so heavily charged with iron ore as to appear nearly opaque. This distinctive mesostasis has been observed in Scottish and Australian undersaturated basic rocks by Balsillie (1922, p. 449), Allen (1924, p. 490), Walker (1930, p. 370; 1936, p. 280), Browne (1927, p. 375) and Benson (1942, p. 166). Lehmann (1930, figs. 3 and 4) has figured almost identical material in the Stöffel essexite porphyries.

THE MODAL VARIATION OF THE TESCHENITES

The teschenites are generally favourable to micrometric measurement. Apart from the coarsergrained modifications from the upper intrusion levels (where modes were carried out on at least two slices from each specimen), the texture on the whole is fairly even, and none of the grains very large. Emphasis was placed on the modal variation of the olivine, clinopyroxene and iron ore. The percentages by volume of these minerals were determined using a point counter (Chayes, 1949; Chayes and Fairbairn, 1951). Modal data on sections A to D and face E are presented in table 2, while table 3 contains the modes of teschenites (traverses F to I) from the roof of the sill. Variation of the modal olivine, clinopyroxene and iron ore is shown graphically in figure 3.

Variation of olivine.—The most olivine-rich facies (B1, D1) contain 23 percent olivine, and all gradations exist between this value and rocks in which olivine is absent e.g. H4, H5. Generally the amount of olivine present is a function of the height of the specimen in the intrusion (fig. 3), although exceptions to this generalization may be noted. Thus B3, D2 and to a lesser extent C1, occurring just below the lower contacts of the slab of Triassic sediments (fig. 2), have a lower olivine content than would be expected from their position in the sill. The discontinuous curve through specimens E2, E4, E7 and E9 is shown because these specimens are more nearly in the same straight line in face E (fig. 2). The general slope of the curves for section A and face E closely approaches the olivine variation diagram for the Garbh Eilean sill (Walker, 1930, fig. 1), although new data on the latter rocks may modify the general trend, especially in the vicinity of the picrite-picrodolerite junction.

Teschenites D5 to D9 serve as a good illustration of the progressive decrease in olivine (10 to 4 percent) with increasing height, as they occur on a continuous face over 70 feet high. Certain rocks from the roof of the sill, e.g. I2, have an olivine content more characteristic of levels 100 feet below. The distribution of olivine in the roof teschenites is slightly irregular (0 to 6 per-

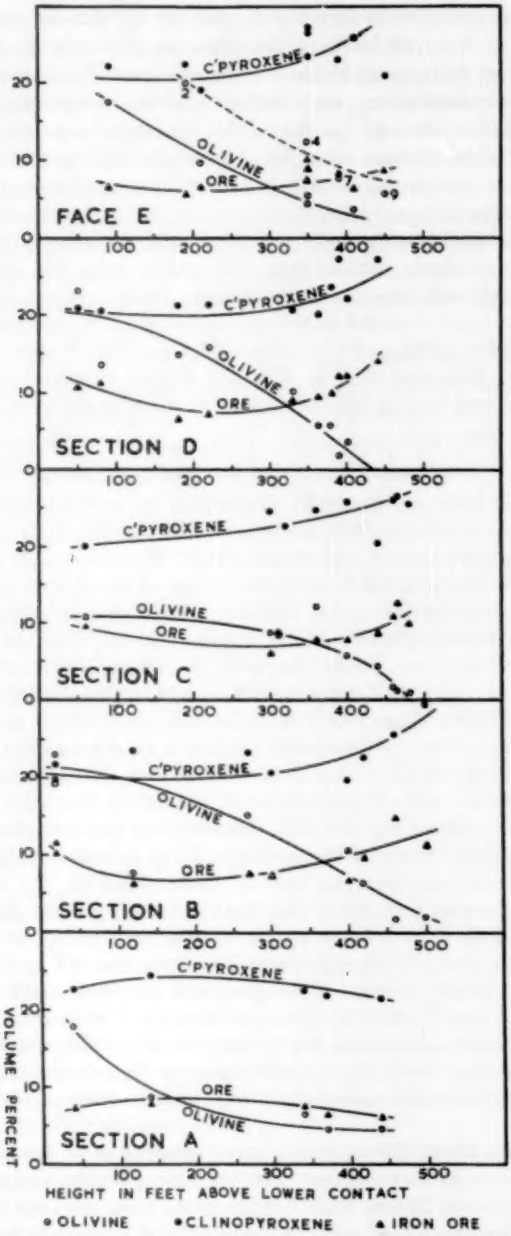


Fig. 3. Modal variation of olivine, clinopyroxene and iron ore in the Black Jack teschenites.

cent), although there is a tendency for the more olivine-poor types to be confined to the central portions of the roof.

In intrusions of alkali olivine basalt type, the closest analogies in modal olivine variation are furnished by the Loch Mealt-Kilt Rock sill (Walker, 1932) and the Circular Head laccolith, Tasmania (Edwards, 1941). The very marked increase in olivine in the central portions, as described in the Saline No. 1 teschenite (Fleet, 1931, fig. 1) and the Mt. Nebo No. 6 sills (Edwards, 1953), is lacking in the Black Jack intrusion.

Variation in clinopyroxene.—With the exception of the teschenites from section A, the amount of modal pyroxene increases with increasing height in the intrusion. On an average, the basal teschenites carry 21 percent pyroxene which increases to values of 26 to 28 percent in the upper rocks. Certain gabbro-teschenites (e.g. H1, H4, H5), containing considerable amounts of mesostasis and zeolite, have a lower pyroxene content than would be average for the intrusion. Of the essential mineral components, the clinopyroxene shows the least relative variation, especially in lateral directions in the sill. The concentration of pyroxene in the upper levels of sills of alkali olivine basalt type has been described or commented on by Allen (1924, p. 494; 1931, p. 314), Flett (1930, p. 70) and Walker (1930, p. 388). In tholeiitic sills, the amount of pyroxene may decrease slightly in the upper levels, e.g. in the Palisades (Walker, 1940, table 1) and Hangnest sills (Walker and Poldervaart, 1941, table IV).

Variation in iron ore.—With the exception of section A, the amount of modal ore decreases at first in the lower teschenites, whence in those rocks at elevations greater than 250 to 300 feet above the lower contacts, it shows a progressive increase. The greatest quantity of ore (14.7 percent) occurs in B8 and I3. With the exception of F4 and H6, the teschenites from the roof of the sill (table 3) are generally richer in opaque oxides than the majority of those teschenites occurring in the first 100 to 150 feet. The amount of iron ore increases in the upper levels of the Lugar (Tyrrell, 1917, p. 117), Garbh Eilean and Fladda sills (Walker, 1930, p. 371; 1931, p. 763), in the upper layered series of the tholeiitic Skaergaard intrusion (Wager and Deer, 1939, fig. 18) and in the upper rocks of the George Washington, Weehawken North (cf. sections B, C, D of the Black Jack sill) and Edgewater sections of the Palisades sill (Walker, 1940, table 1).

Variation in plagioclase feldspar.—No attempt has been made to represent the variation of plagioclase graphically as its widespread analcitization in many rocks results in modal values lower than those originally present. However tables 2 and 3 indicate certain general trends. Up to heights of 350 to 400 feet, there is an increase in the amount of plagioclase feldspar, chiefly at the expense of olivine (see Walker, 1930, p. 371; 1931, p. 763; 1932, p. 249). Above 400 feet, the quantity of plagioclase decreases as zeolite and mesostasis increase, a trend most evident in the gabbro-teschenites, e.g. H7 and H8.

Variation of zeolite and mesostasis.—Little definite can be said about the zeolite trend as no exact data is available on primary and secondary analcite. There is little doubt that the combined zeolite plus mesostasis increases with

increasing height; these two constituents make up nearly 50 percent of gabbro-teschenites H7 and H8. This increase in the amount of alkaline mesostasis with differentiation is analogous with the upward concentration of micro-pegmatite in tholeiitic intrusions e.g. in the Downes Mountain and Hangnest sills (Walker and Poldervaart, 1940, p. 173; 1941, p. 436), the Palisades sill (Walker, 1940, table 1), the Dillsburg sill (Hotz, 1953, table 3) and the Skaergaard intrusion (Wager and Deer, 1939, fig. 18).

Variation in other constituents.—Apatite, present in all the teschenites, is concentrated in the upper gabbro varieties. *Chlorite* and *carbonate* are generally absent for the first 450 feet, and then reveal a trend similar to the apatite. It was not possible to obtain accurate data on the *alkali feldspar*, but visual examination, strengthened by the increase in K_2O in the teschenites with differentiation, suggests its relative concentration in the upper rocks.

ADDITIONAL MINERALOGY

Alteration Products of the Olivines

Bowlingite.—Alteration of the olivine to bowlingite proceeds in a manner analogous to serpentinization. Typical optical properties of the bowlingite are: $\alpha = 1.595$ $\gamma = 1.622$ (± 0.002); pleochroism X = pale green or greenish brown, Z = apple green or golden brown; elongation of fibres positive. The iron content of the bowlingite apparently varies considerably; β ranged from 1.586-1.612 (six determinations). While much of the pale green bowlingite under the microscope strongly resembles serpentine, its refractive index in all instances examined was in the vicinity of $\beta = 1.60$, a value higher than the maximum γ(1.573) of the serpentine minerals (Selfridge, 1936, tables I to IV). During the alteration of the olivines, there is a general absence of the granular stringers of iron ore, of the type precipitated during the serpentinization of dunites and harzburgites, rocks in which the olivines tend to be poorer in fayalite than the olivines in the teschenites. In these rocks, all or most the ore set free is apparently incorporated in the bowlingite, containing $FeO + Fe_2O_3 = 9.89$-13.82 weight percent, according to Caillère (1935). The olivine alteration to bowlingite rather than to serpentine may be a consequence of the highly sodic solutions affecting the alteration. Wells (1929, p. 51-52) could not affect the alteration of olivine to serpentine in the presence of sodic solutions at temperatures and pressures up to 520°C and 267 atm. respectively. In the system $MgO.SiO_2.H_2O$, Bowen and Tuttle (1949, p. 440) demonstrated that below 430°C (at 1500 lbs/in^2) forsterite alters to serpentine (+ brucite); iron-bearing olivines are stable at still lower temperatures.

Iddingsite.—Ruby-red or red-brown iddingsite, second to bowlingite as an olivine alteration product, occurs generally in those teschenites occurring at heights of 450 to 500 feet above the lower contacts. All changes may be traced from incipient iddingsite formation to complete iddingsite pseudomorphs, which may be associated also with released iron ore. Optical properties of iddingsite from H1 are as follows (cf. Ross and Shannon, 1925, p. 14): $\alpha = 1.664$ $\beta = 1.696$ $\gamma = 1.703$ (± 0.003); $\gamma - \alpha = 0.039$; 2V (–) ca. 30-40; pleochroism slight or absent. The increase in the teschenite $\frac{Fe_2O_3}{FeO}$

ratios with differentiation, the increase in the Fe_2O_3 content of the upper titanomagnetites and the iron-charged nature of the mesostasis (Wilkinson, 1957b) indicate that the formation of iddingsite in the upper levels took place in the presence of deuteric iron-enriched solutions, concomitant with increasing oxidation resulting from increased water vapour pressure in a closed magma chamber (cf. Edwards, 1938, p. 280-281). Selecting Fa_{45} as an average minimum composition for the upper olivines, complete oxidation of the available FeO (approximately 38 percent) would result in 42 percent Fe_2O_3 available for iddingsite formation. Ross and Shannon (1925, p. 17) state that the Fe_2O_3 content of iddingsite averages 31 to 32 percent. Any Fe_2O_3 in excess of that necessary for iddingsite may thus be precipitated as ore in the central portions of the iddingsite pseudomorphs.

The Plagioclase Feldspars.—The compositions ($\pm$ 2 *molecular* percent An) of the plagioclase feldspars (tables 2 and 3) refer to mean compositions derived by two methods: (1) measurement of the refractive index (generally the β index) of the central portions of the most widespread feldspar generation; (The resultant compositions in molecular percent anorthite were derived from the data of Chayes (1952), using the conversion scales of Poldervaart (1950, p. 1069). The compositions of the outermost areas in zoned crystals were determined also by refractive index methods.) (2) the measurement of extinction angles (of at least six individuals in the one slice) of albite twin lamellae in the zone normal to (010), using the Rittman zone method, described by Chudoba (1933). Occasional compositional discrepencies of 7 to 8 percent An in the two methods result probably from accumulative inaccuracies in the methods employed, compositional differences between contiguous unzoned lamellae, and the possible non-linear relationship of extinction angles (Crump and Ketner, *in* Emmons, et al., 1953, p. 23).

The most basic plagioclase of average generation is a basic labradorite An_{65} to An_{72} (table 2), a composition comparable with the earliest plagioclase in many tholeiitic sills (Wilkinson, 1956a, table 1). With increasing height above the lower contacts, the plagioclase compositional trend is one of enrichment in albite, the average difference in composition between the upper and lower feldspars being about 11 mol. percent An. This range in composition is not comparable to that exhibited by the associated olivines (Wilkinson, 1956b, table 2). In several teschenites, e.g. A4, B5, E2, F4, the plagioclase tends to be more basic than would be expected from its position in the intrusion. With the presence of considerable alkaline mesostasis in the gabbro-teschenites, the plagioclase increases more noticeably in acidity to composition values between An_{46} and An_{54}. The maximum range in composition between the cores of feldspars is An_{72} to An_{43}, the latter feldspar ($\beta = 1.553$) occurring in micrographic intergrowth with clinopyroxene in H8. As might be expected, refractive index determinations indicate that the plagioclase phenocrysts are more calcic than the average feldspar generation e.g. in C2 and C7, the phenocrysts contain 7 and 5 percent more An respectively than the average feldspar.

A large percentage of the feldspars are zoned, the zoning being the normal progressive type (tables 2 and 3). Oscillatory zoning is much less

common and appears to be confined to phenocrysts, especially those in the basaltic and doleritic teschenites.

No attempt was made to study possible variation of the plagioclase twin laws with differentiation (Chapman, 1936). However a number of twin laws were measured on feldspars selected at random in six teschenites, namely A1, B1 and E1 from the lower levels of the sill, and C9, H1 and H8 from the roof. The total of 65 twins comprised the following:—albite 41; Carlsbad 10; albite-Carlsbad 8; pericline (acline) 3; ala laws 2; Manebach 1. The relative frequencies of the twin laws are similar to those recorded by Chapman (1936) and Gorai (1951, p. 886) for igneous rocks. Although it would be unwise to base any definite conclusions on such limited data, albite-Carlsbad twins appear to be more frequent in the lower levels of the sill.

One notes the contrast in the alteration products of the plagioclase feldspars in the teschenites (analcite and other zeolites), compared with the albite-epidote-zoisite-(grossular) assemblage of saussurite in tholeiitic or calc-alkaline basic rocks. Such contrasting mineralogy may result from: (1) the undersaturated sodic nature of the solutions responsible for the alteration of the alkaline rocks in their later stages of consolidation; (2) the greater stability of the clinopyroxene in the alkaline rocks, which tends to limit the quantity of iron available to the alteration assemblage. During alteration of the olivines, any liberated iron preferably enters either bowlingite or iddingsite.

When the degree of analcitization of the plagioclase in the Black Jack rocks is considered, the late-stage mineralogy does not satisfactorily account for the lime presumably liberated during analcitization. Possibly a certain amount of lime in solution was expelled into the roof rocks in the final stages of consolidation.

Alkali feldspar.—Although alkali feldspar is discernible in nearly all thin-sections, only in specimen I2 is this mineral sufficiently fresh to repay separation. The feldspar was mixed with synthetic spinel $MgAl_2O_4$, and its composition obtained from the X-ray powder photo by the following methods: (1) from the measurement of $d(\bar{2}01)$ (Bowen and Tuttle, 1950, fig. 2) which gave as composition Or_{27} weight percent; (2) by the measurement of the linear distance between the 111 (spinel) and $\bar{2}01$ (feldspar) reflections (Coombs, 1954, p. 423-425), which indicated a composition of Or_{25}. The final composition of the feldspar, *anorthoclase*, was taken as Or_{26} $(Ab + An)_{74}$ weight percent.

The optical properties, indicating a composition Or_{23} to Or_{29} on the graph of Tuttle (1952, p. 559), may be compared with anorthoclase from Victoria, Australia, composition $Or_{23}Ab_{76}An_1$ (chemical analysis; Tuttle, 1952, table 1).

Black Jack anorthoclase	Anorthoclase from Victoria, Australia
$\alpha = 1.525$ (± 0.001)	$\alpha = 1.5253$
$\beta = 1.530$	$\beta = 1.5311$
$\gamma = 1.532$	$\gamma = 1.5321$
$2V_\alpha = 50 - 53°$ $(\pm 1°)$	$2V_\alpha = 47°$

Mean $2V_\alpha$ (five settings) $= 52°$
Optic axial plane $\sim \perp$ (010)

The composition, 2V and position of the optic axial plane identify the feldspar as a member of the sanidine-anorthoclase cryptoperthite series (Tuttle, 1952). On the graph of MacKenzie and Smith (1956, fig. 1), the feldspar is near the boundary of the anorthoclases and anorthoclase-cryptoperthites. While the powder photo indicates a homogeneous feldspar, the spectrometer pattern shows the 201 peak just beginning to split, indicating submicroscopic unmixing.

Analcite.—The analcite is generally isotropic, with n = 1.487 to 1.490. However some of the analcite occurring in vughs reveals fine twinning in weakly birefringent (ca 0.002) units. The mode of occurrence of the birefringent analcite suggests its inversion to a lower symmetry form stable at low temperatures (Coombs, 1955, p. 704). There is no evidence that the optical anomalies have resulted from strain during crystallization (Stewart, 1941, p. 7).

A notable amount of soda in the analcite is replaced by potash (table 5), the replacement being greatest in the analcite from the lower teschenites. In these rocks, replacement of Na (r = 0.98Å) by K (r = 1.33Å) was facilitated by temperatures (Larsen and Buie, 1938, p. 838; Goldschmidt, 1954, p. 140) higher than those in the upper levels of the sill, despite the presence in the latter areas of potash-enriched late stage solutions.

TABLE 5

Alkali Contents of Analcites

Constituent	B1	B4	B7	H8	I	II	III
Na_2O	11.27	12.15	12.50	12.09	10.93	13.31	8.48
K_2O	1.74	1.48	1.06	1.11	1.62	0.73	4.48

B1-H8 Analcites from the Black Jack teschenites.
B1 Teschenite 20 feet above lower contact.
B4 Teschenite 270 feet above lower contact.
B7 Teschenite 420 feet above lower contact.
H8 Teschenite approx. 500 feet above lower contacts.
I Analcite from monzonite, Morotu district, Sakhalin (Yagi, 1953, table 11).
II Analcite from pegmatitic patch in borolanite, Allt a'Mhuillin, Loch Borolan, Assynt (Stewart, 1941, table IV).
III Potash analcite, from analcite-basalt, Highwood Mountains, Montana (Larsen and Buie, 1938, table I).

Textural and mineralogical relations strongly suggest that a large percentage of the analcite is a product of direct magmatic crystallization (cf. Friedman, 1951, p. 26). Its occurrence interstitial to the earlier minerals (especially plagioclase whose margins against the analcite may reveal little or no analcitization), the abundance of inclusions such as apatite and biotite, and most important, the absence in the preceding cases of any evidence suggesting the former presence of another mineral, are relationships indicating a primary origin. However a certain amount of the analcite is secondary, or more strictly deuteric in the original sense of Sederholm (1916, p. 142), arising from the breakdown of the plagioclase (and alkali) feldspars under

the influence of the residual sodic solutions. Much of the vugh analcite is referred to such an origin.

DIFFERENTIATION TRENDS AND COURSE OF CRYSTALLIZATION OF THE TESCHENITES

Eight teschenites from varying levels in the sill were analysed (table 6). After cutting and grinding away the enclosing gabbro-teschenite H4, sufficient of the vein mesostasis was available for both chemical and spectrographic analysis. Except for their relative richness in total iron (13 to 14.5 percent calculated as FeO; cf. Kennedy, 1933, p. 241), the Black Jack teschenites present no noticeable departures in their chemistry from teschenites described elsewhere. The range of the principal oxides between varying limits is a reflection on the varying modal and mineralogical compositions consequent on differentiation. Close mineralogical and chemical similarity is afforded by the mesostasis-bearing Isle of May teschenites (M.P.C.41005-9; table 6, anal. X) and the Stöffel essexite porphyries (M.P.C.71183, 71185-6; table 6, anal. XI). While no suitable petrographic term can be applied to the alkaline vein mesostasis from H4, solely on microscopic examination, its chemistry is distinctive in that it can be matched by analcite syenites occurring as frequent field associates of teschenites and allied rocks in differentiated sills (Wilkinson, 1956a, table 3).

The teschenite differentiation trends.—In figure 4, the weights percent of the principal oxides have been plotted against the ratio $\frac{FeO+Fe_2O_3}{FeO+Fe_2O_3+MgO} \times 100$ (Wager and Deer, 1939; Walker and Poldervaart, 1949), i.e. the Mafic Index (M) of Simpson (1954). This ratio is a measure of the degree of differentiation of basaltic magma (Walker, 1953, p. 49), and yields the best results in the early and middle stages of differentiation. With the exception of B3, the distribution of analyses from left to right in figure 4 coincides with the increasing height of the specimens above the lower contacts.

As in the case of tholeiitic magma (Walker and Poldervaart, 1949, p. 650-654; Tilley, 1950, p. 47), the crystallization of alkali olivine basalt magma broadly involves two series of mineral groups, the mafic (olivines, pyroxenes, etc.) and felsic (chiefly feldspars). In the present discussion, attention is directed also to the changing chemistry of the titanomagnetites with differentiation.

Silica increases significantly only in the latest stages of differentiation (fig. 4). *Alumina* shows a steady increase. Additional analyses may indicate a slight alumina maximum in the middle stages of differentiation, due to the precipitation of increased plagioclase.

Titania increases steadily during differentiation, in harmony with both the maximum development of titanomagnetite in the upper levels of the sill and the increasing titania content of these minerals. The tholeiitic Skaergaard and New Amalfi intrusions reveal a similar trend for TiO_2. The late analcite syenite differentiate H4 reveals marked impoverishment in TiO_2.

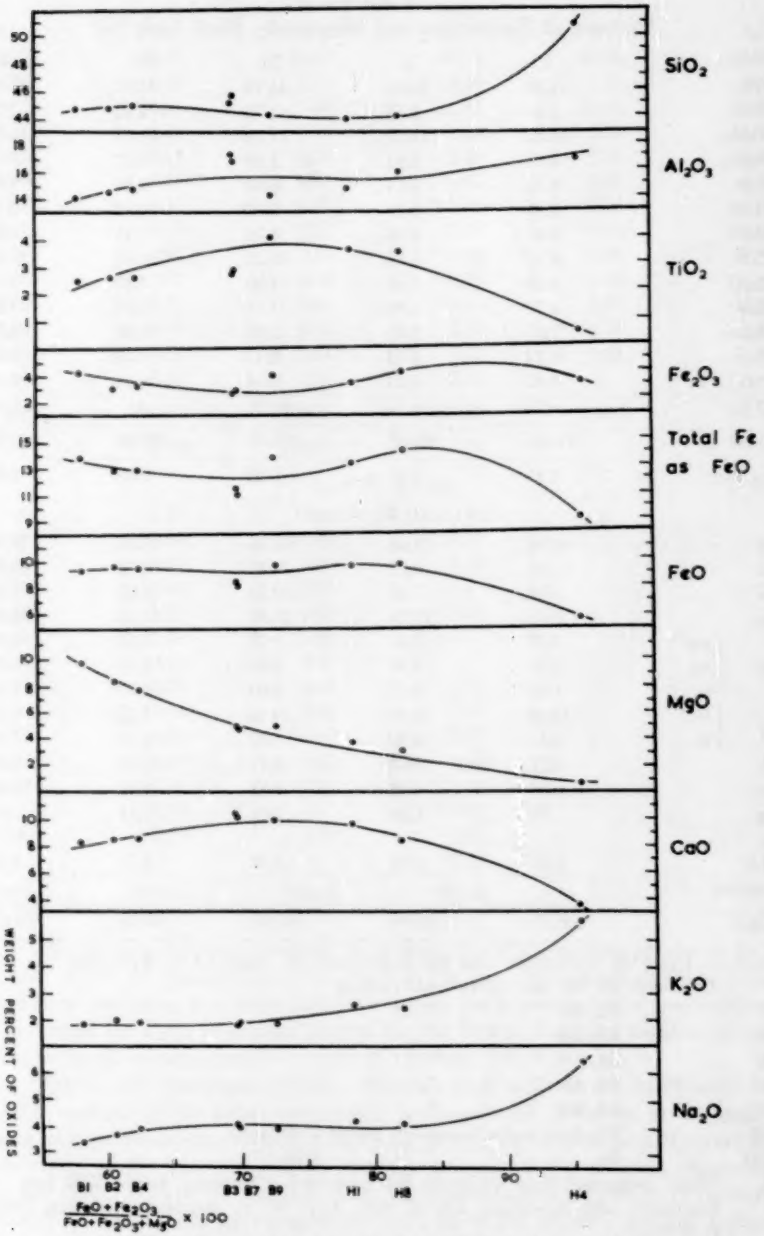


Fig. 4. Differentiation trends of the Black Jack teschenites.

TABLE 6

Analyses of Teschenites and Mesostasis, Black Jack Sill

	I	II	III	IV	V
SiO_2	44.78	44.73	45.15	44.97	45.66
TiO_2	2.49	2.58	2.71	2.62	2.79
Al_2O_3	14.03	14.42	17.29	14.64	16.71
Fe_2O_3	4.15	2.93	2.59	3.12	2.71
FeO	9.15	9.51	8.36	9.28	7.93
MnO	0.14	0.15	0.10	0.12	0.12
MgO	9.57	8.08	4.76	7.45	4.60
CaO	8.12	8.31	10.25	8.33	10.01
Na_2O	3.30	3.60	4.00	3.80	3.94
K_2O	1.77	1.96	1.76	1.81	1.82
H_2O+	2.05	2.89	2.86	2.88	2.84
H_2O-	0.14	0.23	0.13	0.23	0.21
P_2O_5	0.62	0.64	0.44	0.65	0.58
CO_2	nt.fd.	nt.fd.	nt.fd.	tr.	nt.fd.
Total	100.31	100.03	100.40	99.90	99.92
Sp. Gr.	2.95	2.91	2.83	2.86	2.84
		C.I.P.W. Norms			
or	10.56	11.68	10.56	10.56	10.56
ab	18.34	16.77	15.20	19.39	18.86
ne	5.11	7.38	10.22	6.82	7.67
an	18.07	17.24	23.91	17.51	22.80
di wo	7.77	8.47	9.78	8.35	9.74
di en	5.20	4.90	5.50	5.10	5.50
di fs	1.98	3.17	4.09	2.77	3.83
ol fo	13.16	10.50	4.48	9.52	4.20
ol fa	5.71	6.32	3.67	5.71	3.06
il	4.71	5.02	5.17	5.02	5.32
mt	6.03	4.18	3.71	4.41	3.94
ap	1.34	1.34	1.01	1.34	1.34
cc	—	—	—	—	—
H_2O	2.19	3.12	2.99	3.11	3.05
siderite	—	—	—	—	—
Total	100.17	100.09	100.29	99.61	99.87

Analyses I to VIII, teschenites from the Black Jack sill. Anal. J.F.G. Wilkinson.

I Teschenite B1, 20 feet above lower contact.
II " B2, 20 " " " "
III " B3, 120 " " " "
IV " B4, 270 " " " "
V " B7, 420 " " " "
VI " B9, 500 " " " "
VII " H1, from roof of intrusion, height 2140 feet.
VIII " H8, " " " " " 2200 "
IX "Vein" mesostasis from teschenite H4, from roof of intrusion, height 2200 feet.
X Teschenite with mesostasis, Isle of May. Anal. W. H. Herdsman (Walker, 1936, p. 283).
XI Essexite-porphyry, Stöffel, Westerwald. Anal. J. Holzner (Lehmann, 1930, p. 349).

TABLE 6 (Continued)

VI	VII	VIII	IX	X	XI
44.15	43.92	44.01	50.71	46.90	45.03
4.07	3.60	3.53	0.59	1.95	4.02
14.13	14.61	15.90	16.72	16.95	16.91
3.83	3.20	4.15	3.26	3.24	3.59
9.43	9.48	9.57	5.49	5.59	6.00
0.10	0.11	0.08	0.01	0.20	0.16
4.80	3.54	2.97	0.42	5.50	6.14
9.62	9.58	8.17	3.27	8.90	9.50
3.84	4.12	4.05	6.42	3.80	2.96
1.83	2.58	2.40	5.75	1.78	2.84
3.26	3.12	4.04	4.07	3.20	2.39
0.20	0.18	0.31	0.49	1.55	0.89
0.70	0.36	1.21	0.12	0.45	0.09
nt.fd.	1.52	tr.	2.94	—	—
99.96	99.92	100.39	100.26	99.81	100.52
2.90	(2.92)	2.81	2.57		
		C.I.P.W. Norms			
10.56	15.57	14.46	33.92		
19.39	18.34	21.48	33.01		
7.10	8.80	7.10	11.36		
15.85	13.62	17.79	—		
11.37	9.05	6.50	—		
6.70	4.40	3.00	—		
4.09	4.49	3.43	—		
3.78	3.08	3.08	0.70		
2.65	3.47	3.88	3.67		
7.75	6.84	6.69	1.22		
5.57	4.64	6.03	4.87		
1.68	1.01	2.69	0.34		
—	3.40	—	5.50		
3.46	3.30	4.35	4.56		
—	—	—	1.28		
99.95	100.01	100.48	100.43		

Phosphorus behaves similarly to titania. The P_2O_5 content increases by a factor of two in passing from the basic to the basic intermediate teschenites, and then decreases to a value one-fifth that at the beginning of crystallization. This trend for P_2O_5 is similar to that for the British Tertiary alkaline series, olivine basalt → mugearite → trachyte (Richey, 1937).

Ferric iron decreases initially, and then progressively increases until the Fe_2O_3 content of the upper teschenites is comparable to values at the beginning of crystallization. Variation in Fe_2O_3 is correlated with both the varying chemistry of the titanomagnetites and the amount of this mineral separating at any time (Wilkinson, 1957b). After the titanomagnetite of early crystallization, Fe_2O_3 and TiO_2 were constantly built up in the residual liquids. Following the crystallization of iron-rich silicates and iron ores in H8, the residual

liquid (analcite syenite) reveals impoverishment in FeO, Fe_2O_3 and TiO_2. The differentiation trend of Fe_2O_3 in both the Circular Head crinanites (Edwards, 1941, p. 407) and Karroo dolerites (Walker and Poldervaart, 1949, p. 651) closely resembles the ferric iron trend in the teschenites.

Although the upper teschenites reveal slight absolute enrichment in total iron (calculated as FeO), the *ferrous iron* contents of the rocks undergo little variation. However relative enrichment in FeO with respect to MgO is marked, and *magnesia* decreases progressively with differentiation. The FeO/MgO variation is dominated by an ever-diminishing amount of olivine, concomitantly with the progressively more fayalitic nature of this mineral.

The increased amount of plagioclase in the middle stages of differentiation is reflected in an increase in *lime*, after which stage this constituent decreases, due to both the more sodic nature of the plagioclase and a decrease in modal plagioclase.

The Black Jack trend of *alkali enrichment* in the later stages of differentiation is shown by many other sills of alkali olivine basalt and tholeiitic parentage e.g. the Circular Head (Edwards, 1941), Braefoot (Campbell, Day and Stenhouse, 1932), Dillsburg (Hotz, 1953) and Northfield sills (Walker, 1952). In the teschenites, potash increases at a more rapid rate than soda, as a result of the incoming of alkali feldspar in excess of increasing amounts of sodic zeolite and a progressively Ab-enriched plagioclase.

In general the differentiation trends exhibited by the Black Jack teschenites are the same as the trends resulting from the plot of 83 analyses of Karroo dolerites (Walker and Poldervaart, 1949, fig. 26).

The dominant trend in the early and middle stages of differentiation is one of relative enrichment in iron with respect to magnesia. Once initiated, the effects of alkali enrichment (particularly in the residual liquids) overshadow any other trends which may be operative during the final stages of differentiation. The composition of the analcite syenite mesostasis (a very small volume of the total intrusion) illustrates a principle emphasized by Wager and Deer (1939, p. 236) and Hotz (1953, p. 702), namely that the maximum compositional changes brought about by differentiating basaltic magma occur only after crystallization of 75 to 85 percent of its volume. In both alkali olivine basalt and tholeiitic magmas, the effect generally results in an abrupt change in rock types.

Course of crystallization.—The teschenite course of crystallization has been represented on an alkali-total iron-magnesia diagram (fig. 5).[2] The curve illustrating the course of crystallization is concave downwards. In the early stages, the trend is one of relative iron enrichment with respect to magnesia as the amount of modal olivine decreases, simultaneously with its more fayalitic nature; the clinopyroxene undergoes little compositional change. The enrichment in alkalies exhibited by the analcite syenite mesostasis is illustrated by the crystallization course at the apex of iron enrichment taking an abrupt plunge to the Na_2O+K_2O corner. The Black Jack sill yields information on the trends of basic representatives of alkali olivine basalt magma. Yagi's in-

[2] The variation diagram for the teschenites on a basis of Mg, $(Fe^{2+}+Fe^{3+})$, and (Na+K) will be presented in a subsequent paper (cf. Nockolds and Allen, 1954).

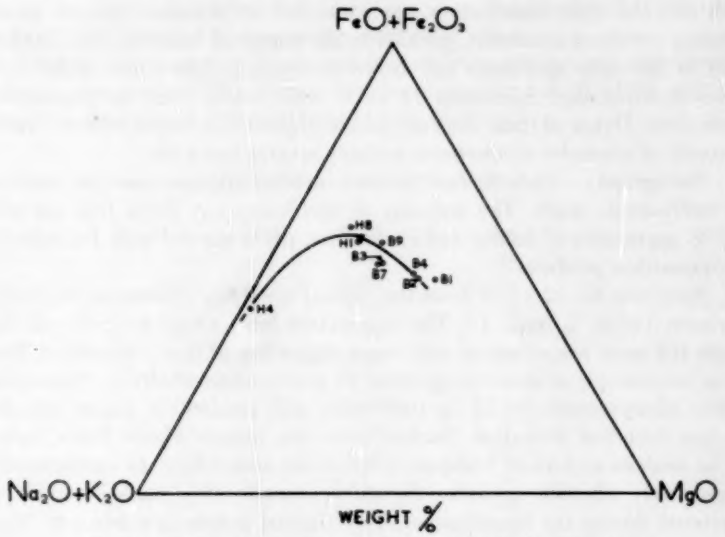


Fig. 5. Course of crystallization of the Black Jack teschenites.

vestigations of the Morotu co-magmatic alkaline series (analcite dolerites, monzonites, syenites) provide the necessary stability to the crystallization course in the later stages of differentiation. The majority of the more alkaline types from Morotu plot in the vicinity of the join between H8 and H4 (Yagi, 1953, fig. 16).

It appears that the over-all courses of crystallization of hypabyssal representatives of both alkali olivine basalt and tholeiitic magma do not differ in their fundamental aspects (Walker, 1952, fig. 2; 1953, fig. 3), although responses to varying degrees of iron enrichment (particularly absolute iron enrichment in certain tholeiitic series) may result in the displacement of a particular series from an optimum mean trend (Nockolds and Allen, 1956, figs. 31 to 38). Such displacement probably results from the response of the varying chemistry and position in the crystallization sequence of the opaque oxides to prevailing oxidation-reduction equilibria. Depending on these factors and the amount of preliminary differentiation at depth, a series of co-magmatic sills may continue their normal trend of crystallization along slightly different paths (e.g. the diabase sills at Duluth, Minnesota, described by Schwartz and Sandberg, 1940).

THE FEEDER DYKES

Although the colliery workings below the sill provided excellent opportunity to study the feeders, this study was unfortunately limited in its scope, as the majority of the dykes have been intensely altered to the "white trap" of the Scottish petrologists (Flett, in Peach et al, 1910, p. 311-313; Day, 1928; Tyrrell, 1952, p. 376). Extrapolation of outcrops in the workings indi-

cates that the dyke distribution was controlled by a major fracture pattern trending northeast-southwest, parallel to the marginal faults (p. 4). The locations of the dyke specimens are shown in figure 2. The width of the dykes varies considerably. Specimens J1 to J3 were taken from an exposure 20 yards wide. Dykes of these dimensions are regarded as major feeders, and the majority of examples encountered are only several feet wide.

Petrography.—Only in rare instances are the original minerals preserved for microscopic study. The majority of specimens, e.g. J9 to J12, are white friable aggregates of kaolin and carbonates, often stained with ferruginuous decomposition products.

Specimen J5, 12 yards from the edge of the dyke, represents the freshest specimen (table 7, anal. I). The plagioclase laths (An_{60} to An_{65}; average length 0.3 mm) are arranged with some suggestion of flow orientation. There is no microscopic evidence suggesting J5 ever contained olivine. Sub-ophitic mauve clinopyroxene (0.15 by 0.03 mm) still persists, in places revealing spongey incipient alteration. Skeletal iron ore, minute biotite flakes, apatite fibres, analcite and alkali feldspar complete the assemblage. J4 (unfortunately considerably altered) provides the only example of a chilled margin encountered during the investigation. The original porphyritic feldspar (up to 1.6 by 0.4 mm) is now represented entirely by calcite. The only recognizable minerals in the clouded microcrystalline chilled groundmass are feldspar microlites and rare grains of iron ore.

Relict microscopic structures in some specimens, e.g. J1, J2, J13 indicate they were originally porphyritic in olivine. Typical idiomorphic olivine outlines are now represented by carbonate (Jevons, et al, 1911, p. 485; Scott, in Gibson et al, 1925, p. 95), quartz and indeterminate dusty alteration products. J2 was originally comparatively rich in olivine (10 to 15 percent). Fresh clinopyroxene or evidence of its former presence is absent in J1 to J3; occasional feldspar "ghosts" are represented by calcite and kaolin. In strong contrast to its instability in the teschenites in the main sill, plagioclase is the mineral in the dykes least susceptible to alteration.

In the most intensely altered feeders, the bulk of the thin section is made up of near-opaque brown kaolin, sometimes pierced by feldspar "ghosts" and interstitial areas of carbonate. A large proportion of the carbonate is calcite, with $\omega = 1.655$ to 1.659. J7 contains a carbonate close to siderite, with $\varepsilon = 1.619$ (Winchell and Winchell, 1950, p. 110). Infillings of chalcedonic silica ($\varepsilon = 1.540$) are sometimes encountered but are rare.

Chemistry.—Only J5 was sufficiently fresh to repay analysis (table 7, anal. I). Despite the presence of 7.25 percent CO_2, the chemistry of J5 indicates its teschenitic affinities. However the MgO and K_2O contents are comparable with those of teschenites occurring in the upper levels of the sill (table 6). A small amount of mesostasis is present in J5. Another noteworthy feature is the Fe_2O_3/FeO ratio, which is lower than this ratio for any of the teschenites in the main sill. Day (1928) has given a clear account of the principal chemical changes involved in the formation of "white trap". In the

case of J5, the main change has been one of carbonation, with little or no increase in the alumina content at the expense of silica.

Perhaps the most important point arising from microscopic and chemical study[3] of the feeder dykes is that they were emplaced at differing stages in relation to the over-all differentiation history of the sill.

TABLE 7
Analysis of Teschenite Dyke

	I	II		Norm of I
SiO_2	43.38	36.48	or	16.12
TiO_2	2.02	1.64	ab	18.34
Al_2O_3	15.39	13.36	ne	6.25
Fe_2O_3	2.03	1.36	an	18.07
FeO	8.32	9.44	di wo	5.80
MnO	0.09	0.26	di en	2.80
MgO	4.08	3.14	di fs	2.90
CaO	7.09	10.06	ol fo	5.04
Na_2O	3.57	3.34	ol fa	5.71
K_2O	2.70	0.28	il	3.80
H_2O+	1.83	3.14	mt	3.02
H_2O-	1.59		ap	1.34
P_2O_5	0.53	0.39	cc	—
CO_2	7.25	16.53	H_2O	3.42
etc.	—	0.73	CO_2	7.25
Total	99.87	100.15		99.86
Sp. Gr.	2.77	—		
$\frac{Fe_2O_3}{FeO}$	0.24	—		

I Carbonated teschenite dyke J5, colliery workings, Black Jack. Anal. J.F.G.W. (for location, see fig. 2).
II "White trap", Granton, Scotland. Anal. T. C. Day (Day, 1928, p. 194).

Inclusions.—It is only in the feeder dykes that one encounters material foreign to the teschenite suite. The largest inclusion (one foot in diameter) was collected at the outcrop of specimens J4-J8. The inclusion is a typical greywacke, with angular grains of quartz and feldspar (microline and oligoclase An_{20}) set in a matrix of brown kaolin, sericite and finely chopped-up quartz. This inclusion shows no evidence of metamorphic modification or incorporation. Smaller inclusions of siliceous shale are present in J8, and present straight boundaries to the enclosing teschenite. Xenocrysts of quartz and microcline are also present in some sections.

PETROGENESIS OF THE TESCHENITES AND ASSOCIATED ANALCITE SYENITE

Generalised outline of the evolution of the sill.—After the injection of the magma into the cold country rock, the formation of a chilled envelope probably occurred, inside which cooling proceeded fairly rapidly. Erosion has removed all evidence of the chilled selvage from the walls and roof of the sill. One page 5, the difficulties in collecting chilled margins from the lower contacts were enumerated. From the porphyritic nature of some of the feeder

[3] Trace element data on J5, J6 and J13, compared with the rocks of the main sill, is consistent with this view.

dykes, it is assumed that the original magma at the time of intrusion was not completely liquid, but that olivine and plagioclase had begun to crystallize. Glassy selvages of similar rock types indicate an early crystallization of these minerals (Campbell, Day and Stenhouse, 1932, p. 346; Edwards, 1941, p. 408).

Teschenite B2 is assumed to have a composition close to that of the parental magma.[4] The composition of B2 (recalculated 100 percent anhydrous) is presented in table 8, where it is compared with other parental magmas of alkali olivine basalt type. The composition of the most olivine-rich teschenite, B1 (table 8, anal. I), imposes no difficulties on the concept of its crystallization from a melt of similar composition (table 8, anal. III and IV).

The intrusion of the Black Jack magma resulted primarily from aggressive vertical igneous forces when the energy in the magma reservoir was sufficient to force the magma into position. In the teschenites of the main sill, the absence of foreign material and abnormal rock types as a result of assimilative action would indicate that the intrusive magma acted as wedge, forcing the sediments apart. The absence of any significant folding in the surrounding sediments excludes the application of horizontal (tangential) forces which would have arched the sediments, thus enabling the magma to flow in passively.

The marginal faults of small displacement probably represent the fractures which preceded the opening up of the main southwest-northeast fracture pattern, culminating in the injection of the main body of magma.

After intrusion, the Black Jack magma crystallized under hypabyssal and hence rather different physical conditions. While it does not appear possible to accurately ascertain the thickness of the sedimentary cover at the time of intrusion, this is thought not to have been great, possibly of the order of a couple of hundred feet. Relatively rapid cooling at high crustal levels is indicated by the essentially homogeneous nature of certain mineral phases (titanomagnetites and alkali feldspar) which under conditions of slow cooling are prone to unmix readily.

Along with the small amounts of already crystallized olivine and plagioclase feldspar, titanomagnetite was an early precipitation mineral in the lower teschenites. In the middle and late stages of consolidation, the titanomagnetite generally crystallized late. In the lower teschenites, pyroxene crystallized soon after olivine, plagioclase and titanomagnetite, but once initiated, the rate of growth of this mineral was rapid, exceeding that of plagioclase. Although some of the latter mineral crystallized before pyroxene, it is likely that a large proportion of the two minerals crystallized simultaneously (Bowen, 1928, p. 68). The third generation of plagioclase microlites points to the continued crystallization of feldspar after cessation of the bulk of the clinopyroxene. Even in the early stages of consolidation, a highly alkaline residuum was produced which either crystallized interstitially as microcrystalline mesostasis, or else precipitated analcite and other zeolites.

[4] From B2, the major and trace elements of successive teschenites are fairly smooth along a supposed liquid line of descent (cf. Nockolds and Mitchell, 1948).

The migration of this alkaline residuum resulted in the upper gabbro-teschenites crystallizing in a water-rich alkali silicate environment. These conditions were advantageous to both free- and skeletal-growth (particularly in the case of the olivine, clinopyroxene and titanomagnetite), and the production of a progressively coarser grain size. Much of the olivine in these gabbro-teschenites crystallized after feldspar and clinopyroxene. Although a mineral of long crystallization range, apatite in these upper rocks preferentially separated at a late stage. The analcitization of the plagioclase, the kaolinization of the alkali feldspar, the formation of biotite marginal to the titanomagnetites, the leucoxenization of the iron ores, and the development of minor rims of green sodic clinopyroxene around the titaniferous salites provide evidence of the activity of the residual solutions, in some cases iron-rich. The alkaline residuum finally crystallized as a microcrystalline aggregate of alkali feldspar, pyroxene and analcite.

The differentiation mechanism.—Any proposed differentiation mechanism must be based fundamentally on the integration of the modal and chemical (major and minor element) variation of the teschenites, and the compositions of their constituent minerals. Basic data along these lines are as follows:

(1) The general variation in the modal percentages of the principal mineral series is of a continuous type.

(2) With increasing height above the lower contacts, the olivine changes from Fa_{21} to Fa_{60} while the plagioclase changes from An_{72} to An_{43}. At the same time, the analysed bulk clinopyroxene undergoes only a slight compositional change, $Ca_{48}\ Mg_{37}\ Fe_{15}$ to $Ca_{47}\ Mg_{34}\ Fe_{19}$ (Wilkinson, 1957a).

(3) These compositional trends are consistent with the crystallization of these minerals from regions of high to lower temperatures. The trend of the associated titanomagnetites is also consistent with decreasing temperature (Wilkinson, 1957b, fig. 3). Higher temperatures at the base of the sill resulted in increased substitution of potassium for sodium in the analcites from these levels.

(4) It is concluded that the order of consolidation of the sill was from the base upwards.

(5) In a general way, this sequence of consolidation parallels well-defined differentiation trends in the rock series.

It is considered that the mechanism of *fractional crystallization*, i.e. the separation of successive crystal fractions from liquids of ever-changing composition, is the only mechanism based on sound experimental data which can adequately explain the progressive variations (compositional, mineralogical and chemical)[5] within the sill. The teschenites lend themselves favourably to crystal fractionation since they are composed of the same minerals in differing relative proportions. That the sill differentiated predominantly *in situ* is indicated by the variable amounts of the principal mineral series maintaining a more or less uniform lateral distribution. From the base to the top of the sill,

[5] A study of the trace element distribution in both the rock and mineral series lends strong support to crystal fractionation as the predominating differentiation mechanism.

the sequence of mineral assemblages may be likened to successive crystal fractions separating from a magma of ever-changing composition.

The crystallization of the magma was dominated by the mineral series, olivines, clinopyroxenes, plagioclase feldspars and titanomagnetites, each in itself a continuous reaction series. The principal variations of the rocks on variation diagrams are adequately explained by the olivines dominating the enrichment in iron relative to magnesia in the early and middle stages of consolidation, followed by ever-increasing alkali enrichment in the feldspars. When the compositions of co-existing olivines and plagioclases are referred to their respective phase diagrams, the olivine is seen to crystallize at the higher temperature. Hence with falling temperature, the amount of magnesia (the highest melting component) decreases, resulting in less olivine being precipitated, simultaneously with the more fayalitic nature of successive crops of crystals, as each liquid of changing composition precipitated its solute under the prevailing temperature conditions. Differentiation was accentuated by the prominent zoning in the olivines, clinopyroxenes and plagioclases, indicative of failure of attainment of equilibrium of these minerals with the ever-changing liquids.

While the distribution of the olivine and plagioclase compositions in relation to the principal compositional trends is consistent with the concept that the bulk of the sill was emplaced as the result of one principal magmatic injection (probably through several feeders), the presence of relatively basic olivines and plagioclases at high levels in the sill indicate later pulses of relatively undifferentiated magma. On the other hand, preliminary differentiation of an advanced type is indicated by the chemistry of certain of the feeder dykes (see p. 26).

No evidence of liquid immiscibility, assimiliation or gaseous transfer as differentiation mechanisms has been observed *within the rocks themselves.*

The possible role of gravtitative accumulation.—For progressive fractional crystallization, various mechanical processes have been proposed whereby physical separation occurs between the crystals and ever-changing liquids. Filter-press action is effective only when a large percentage of the intrusion has solidified. In the early and middle stages of crystallization, the movement and subsequent accumulation of certain crystals (olivine, pyroxenes and iron ores) under the influence of gravity has been the process to which the greatest appeal has been made. The petrogenesis of basic hypabyssal rocks enriched in these minerals has been cited frequently as due simply to "gravitative accumulation" or "the movement of the crystals under gravity." Fenner (1929, p. 224) and recently Drever (1952) have critically reviewed the limitations of such a process. Although the successive fractions of the Black Jack magma occur one above the other, it is thought that such a distribution does not necessarily involve the movement of crystals (especially olivine) under the influence of gravity. It is true, as Bowen says, that "gravity never takes a holiday", but factors opposing the gravitative effect may predominate. The following points should be considered:

(1) The composition of the most olivine-rich facies B1 imposes little difficulty on the concept of its derivation from a melt of approximately the

same composition (table 8) and fulfilling the compositional requirements of a parental magma. Moreover there is no great departure (indicative of accumulative facies) in the chemical and mineralogical composition of any rock from the trend representative of a series of liquids.

(2) It has been argued that the density of rocks from successive levels should decrease upwards in differentiated sills, if gravity plays any part in the differentiation process. Table 2 indicates that rocks from the uppermost portions of the sill possess specific gravities comparable to those at the base. The specific gravity is of course only a reflection on the percentage of ferriferous minerals present in the rock, a point emphasized by Wager and Deer (1939, p. 84), and is controlled in many cases by factors more fundamental than crystal sinking.

(3) Both iron ore and clinopyroxene are more abundant in the upper levels of the sill than in the lower rocks. It has been concluded that the amounts of modal clinopyroxene and iron ore have been controlled essentially by the changing chemistry of these minerals and the magma, and the positions of the minerals in the crystallization sequence (Wilkinson, 1957a, 1957b). Moreover it is difficult to see why preferential sinking of olivine rather than clinopyroxene is advocated so frequently, as their specific gravities in the early stages of differentiation (olivine Fa_{15} 3.46; clinopyroxene 3.40 to 3.42) are little different in relation to all the complex factors present in the crystallizing magma.

TABLE 8

Compositions of Parental Magmas of Alkali Olivine Basalt Type
(Recalculated 100 percent anhydrous)

	I	II	III	IV	V	VI
SiO_2	45.7	46.2	46.1	45.3	45.8	48.2
TiO_2	2.5	2.7	2.5	2.2	2.3	2.4
Al_2O_3	14.3	14.9	15.1	15.3	16.6	15.9
Fe_2O_3	4.2	3.0	3.0	3.0	4.6	3.6
FeO	9.3	9.8	10.4	10.2	8.6	9.3
MnO	0.14	0.16	0.23	0.20	0.11	0.20
MgO	9.8	8.3	10.4	8.7	7.9	7.4
CaO	8.3	8.6	9.3	11.2	8.4	8.6
Na_2O	3.4	3.7	2.5	3.0	3.8	3.1
K_2O	1.8	2.0	0.3	0.6	1.2	1.0
P_2O_5	0.63	0.66	0.22	0.29	0.71	0.3

I Teschenite B1, 20 feet above lower contact, Black Jack sill.

II Teschenite B2, 20 feet above lower contact, Black Jack sill. (Taken as approximating to the parental magma).

III Scottish Tertiary basalt→ trachyte series. (Average of four analyses; Nockolds and Allen, 1954, p. 282).

IV Younger basalt of Later Series, Mauritius (Average of four analyses. Data from Walker and Nicolaysen, 1954; composition of parental magma from Nockolds and Allen, op. cit.).

V Chilled base of Circular Head laccolith, Tasmania (Edwards, 1941, p. 407).

VI Chilled "olivine basalt" near the base of the Braefoot Outer Sill, Fife (Campbell, Day and Stenhouse, 1932, p. 349).

(4) The rate of cooling of the sill must have been sufficiently rapid to be prohibitive to any significant downward movement of crystals, for the relatively homogeneous state of the titanomagnetites and anorthoclase is comparable to the state of these minerals in a lava. Harker (1909, p. 322) has emphasized the time element in crystal settling, pointing out its general ineffectiveness in sills.

(5) In addition to the time factor, mutual crystal interference must have considerably retarded any tendency towards gravitative settling. The relative concentration of clinopyroxene in the upper teschenites may have been aided by the elongation of the pyroxene crystals. The effects of plagioclase interference are probably more important, especially where the pyroxene reveals ophitic or sub-ophitic relations. The occurrence of glomero-porphyritic clinopyroxene has not resulted in abnormal concentrations in the lower 300 to 400 feet of the sill. In addition, a large percentage of the olivines are sub-ophitic or partially intersertal to feldspar. In their relations to crystal settling, the prohibitive effects of interlocking feldspar are probably of more importance than the volatile constituents in lowering the viscosity of the magma to aid crystal settling. This applies particularly to the upper levels of the intrusion.

(6) If appreciable crystal settling of olivine occurred, one would expect to find crops of olivines which, having completed their crystallization in regions of lower temperature, would show compositions more fayalitic than the average olivines of the rock. Of the many examined optically, only one olivine in B1 fulfilled the above requirements for crystal settling inasmuch as its dimensions and fayalite content are both greater than these values in the associated olivines. The normal zoning consistently shown by the olivines is in agreement with the concept of their having crystallized essentially in situ. Compositional data indicates that successive crops of olivines in the one rock (in terms of differing generations) are successively slightly richer in fayalite (Wilkinson, 1956b). There is no evidence of magmatic resorption in the olivines in the lower teschenites.

Some downward movement of clinopyroxene has been postulated to suggest a mechanism for frequent clinopyroxene reversed zoning (Wilkinson, 1957a). This movement must have been small for two reasons. Firstly, the olivines enclosed poecilitically in clinopyroxene are slightly more forsterite-rich than the average olivines in the rock. Secondly, there are no abnormalties in the modal clinopyroxene in the lower teschenites.

(7) In two cases (specimens B3 and D2) the modal olivine of the teschenites below the slab of Triassic sediments on the eastern margins of the sill is less than would be expected from their position in the intrusion (fig. 3). It might be suggested that these sediments had interfered with crystal settling. However the necessary complementary accumulation of olivine above the sediments is absent, for the teschenites at these heights continue the modal olivine trend of the lower levels. Moreover, the olivine contents of the teschenites above the layer of sediments are comparable with those of teschenites at similar heights where the sediments are absent. Nor do the olivines above and below the sediments reveal any compositional abnormalities away from the general trend. The presence of the Triassic sediments may have resulted

in the teschenites below completing their crystallization in an area of the sill which would be regarded as a partially partitioned-off chamber, so that their modal olivine dropped to low values at an early stage, compared with the entire cooling history of the sill. It will be noted that B3, just below the sedimentary layer, reveals an abnormal early enrichment in soda (table 6, anal. III).

It is not thought that the slab of Triassic sediments (half a mile in length, with an average thickness of 100 feet) was floated up by the magma. It shows no tilting away from the near-horizontal nature of the enclosing sediments, while its position accords with the position to be expected when compared with similar sediments on the opposite side of the sill. The slab of Triassic sediments is believed to represent a portion of the intruded sediments which projected inwards into the sill, while the sediments above were wedged upwards by the intrusive magma. Incomplete erosion of the enclosing sediments has resulted in its preservation at levels above the lower contacts.

As a result of the foregoing discussion, rather than invoke downward gravitative movement of crystals as a significant factor in the evolution of the sill, the Black Jack intrusion is regarded as having crystallized essentially in situ, the residual liquids at any stage having been displaced upwards relative to the successive crystal fractions.

The petrogenesis of the analcite syenite.—The occurence of analcite syenite with basic alkaline rocks in the one intrusion is not an infrequent one. It is analogous to the trachyte-alkali olivine basalt association of the oceanic islands and in intrusive tholeiitic magma finds its parallelism in the dolerite (gabbro)-granophyre association. The general features of the analcite syenite-alkali olivine basalt association have been summarized by Yagi (1953, p. 805). Despite Fenner's (1929; 1931) assertions to the contrary, opinion is fairly general that such felsic bodies represent residual liquids of the parental basic magma (Ichimura, 1924, p. 103; Gilluly, 1927, p. 208; Tyrrell, 1928, p. 565 and 1948, p. 197; Walker, 1930, p. 389; Yagi, 1953, p. 806), although in some cases it is questioned whether the differentiation occurred *in situ*, or in a more deep-seated magma chamber (Gilluly, 1927, p. 209; Raggatt and Whitworth, 1932, p. 229; Edwards, 1935, p. 24).

The study of the alkaline mesostasis (analcite syenite) in the Black Jack teschenites yields strong evidence that analcite syenites can be referred to the consolidation of residual liquids produced as a result of fractionation crystallization within the one igneous body. The following evidence may be noted: (1) the distribution of the mesostasis interstitial to the principal minerals in teschenites representing all stages in the differentiation of the sill, accords well with the concept of its generation in situ; (2) the chemistry of the mesostasis (despite its microcrystalline nature) reveals a composition close to those compositions of medium- to coarse-grained analcite syenites. A mesostasis of this type is not infrequent in undersaturated basic alkaline rocks (p. 13); (3) the major and minor elements of the mesostasis lend strong support to the microscopic evidence that it is a residual liquid.

The mesostasis conforms in its composition to the chemistry of a residual liquid in a differentiation series dominated in the later stages by fractionation

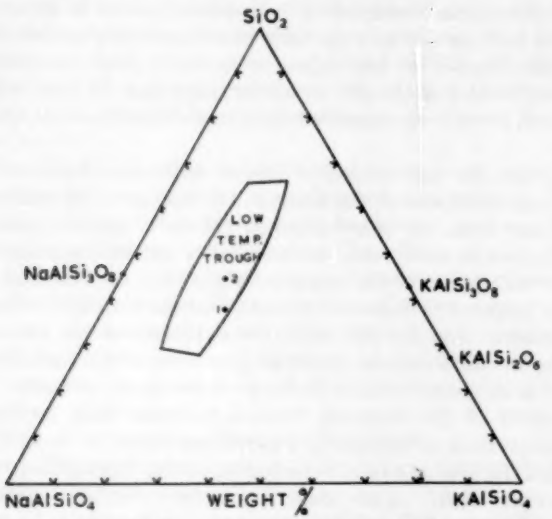


Fig. 6. Compositions of salic portions (less anorthite) of analcite syenites showing their relation to the low temperature trough for the system $NaAlSiO_4$.$KAlSiO_4$.SiO_2.

1. Mesostasis from teschenite H4, Black Jack sill.
2. Ten analcite syenites.

of alkali feldspar. It plots within the low temperature trough of the system $NaAlSiO_4$.$KAlSiO_4$.SiO_2 (fig. 6). The point representing the average of 10 analcite syenites plots very close to the mean of 32 alkaline syenites and 19 alkaline trachytes (after Daly), (Bowen, 1937, fig. 10). Bowen (1937, fig. 10), Benson (1941, fig. 3), Walker and Nicolaysen, (1954, fig. 9), and Yagi (1953, fig. 17) have successfully applied this line of investigation to alkali olivine basalt differentiates. The trace elements of the mesostasis are also consistent with its residual nature. V, Cr, Ni and Co are absent while Ba, Rb, Sr and Zr reveal marked increases, compared with the minor element trends in the teschenite sequence. The tholeiitic Kinkell residuum presents similar minor element analogies (Walker, Vincent and Mitchell, 1952, p. 902). It should be noted that certain syenites associated with analcite-bearing basic rocks contain both modal and normative quartz (cf. Campbell, Day and Stenhouse, 1932, p. 366-368; Raggatt and Whitworth, 1932, p. 222, p. 226). Such occurrences are worthy of closer examination as they may represent the divergency of differentiating alkali olivine basalt to an acidic liquid (Tilley, 1950, p. 43).

Feldspar fractionation ultimately prevailed over ferromagnesian fractionation in the residual liquids (cf. Fenner, 1931, p. 549). In the basaltic and doleritic teschenites constituting the bulk of the sill, the olivines change in composition from Fa_{21} to $Fa_{45\text{-}50}$ while the associated plagioclase varies from An_{70} to An_{60}. These are average figures. Olivine zoning, indicative of iron enrichment, is much more marked than feldspar zoning. However in certain of the upper gabbro-teschenites which represent the latest basic differentiates, the plagioclase feldspars change rather abruptly in composition

to An_{46} to An_{50}. These rocks contain considerable amounts of mesostasis and their chemistry reveals the initial stages of alkali enrichment asserting itself over iron enrichment, a trend which reaches its maximum development in the last magmatic fraction, the alkali-rich vein mesostasis. The composition of the mesostasis shows a decrease in total iron (a feature exhibited also by the Kinkell and Kap Daussy tholeiitic residua) but continues the increase in the FeO/MgO ratio. The acidic nature of the plagioclase (An_{46}) in the host teschenite indicates its late position in the differentiation history.

It is important to distinguish the residual products of basic magma preserved at differing stages in its evolution. If the iron-charged mesostasis of certain teschenites, e.g. I3 could be isolated for analysis, it is likely that its chemistry would reveal the enrichment in iron advocated by Fenner. The Kinkell and Kap Daussy tholeiitic residua differ in their iron and alkali contents. The former glass, richer in alkalies and poorer in iron, plots closer to the alkali corner of an AFM diagram and represents a more advanced magmatic product (Walker, Vincent and Mitchell, 1952, fig. 2). Additional analyses of similar residua from basic rocks will no doubt reveal in their chemistry a continuous trend from the maximum degree of iron enrichment to a product enriched in alkalies, i.e. the trend recognized in the actual rock series themselves.

During the crystallization of the Black Jack sill, the absence of crystal settling and deformative forces affecting the sill were favorable for producing in the later stages of evolution "a mass showing the last liquid as an upper layer and also as an interstitial material in part of rest of the mass" (Bowen, 1919, p. 405-406). It is the latter half of Bowen's statement that is especially applicable to the present discussion, for the residual liquids tended to migrate into the upper intrusion levels as the magma in the lower portions was represented by successive crystal fractions. Various mechanisms have been proposed to explain concentration of the residual liquids which ultimately crystallize as coarse-grained intrusive analcite syenite, namely squeezing of the residual liquid into arch-type cavities produced by lateral thrusting of the intrusion (Bowen, 1919, p. 407), downward pressure of the superincumbent rock during crystallization (Tyrrell, 1928, p. 565) and auto-intrusion as the result of the expansive force of volatiles just prior to final consolidation (Bailey, in discussion in Tyrrell, 1928, p. 568).

In the final stages of crystallization, certain of the gabbro-teschenites may be regarded in terms of crystals of clinopyroxene, feldspar and iron ore immersed in an equivalent volume of residual liquid. The retention of this liquid as mesostasis rather than its concentration to form internal bodies of analcite syenite (or by active compression with subsequent extrusion to yield a small flow of phonolitic composition) seems to have resulted principally from the sill consolidating under a relatively thin sedimentary cover, which resulted in an accelerated rate of cooling. There is no evidence of lateral thrusting in the sediments surrounding the sill. Since analcite syenites occur *within* the intrusions, tensional forces rifting apart the late-stage crystal mush would seem to be an essential feature of their genesis. In many teschenite slices, e.g. A3, A4, B4, B6, D2, D4 and D7 the cross-cutting veinlets of

mesostasis and analcite which traverse fractured crystals of the earlier minerals, which themselves show a neat fit on either side of the veinlets, represent embryonic analcite syenite injections. The attitudes of the minerals bordering these veinlets suggest fracture by tensional forces at a late stage in the cooling history. Such tensional forces may have arisen from the opening up of new feeder dykes below the intrusion, which resulted in slight magmatic pulses at a stage when the crystallization of the main sill was sufficiently advanced to impart to it a certain amount of rigidity.

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THE SOLUBILITY OF QUARTZ IN WATER AT HIGH TEMPERATURES AND PRESSURES

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ABSTRACT. A theoretical equation for the solubility of quartz in supercritical water is set up, the chemical potentials of the participating components being evaluated by methods of statistical mechanics. The equation is fitted to the experimental quartz solubility data of G. C. Kennedy, which extend up to 580°C and 1750 bars. Although the solution mechanism is indeterminate, it is seen that complex, hydrated molecules (probably polymers of H_4SiO_4) are involved at pressures greater than about 500 bars. These molecules dissociate at lower pressures, and further polymerize at higher pressures.

The solubility equation is fitted to one particular solution mechanism, which holds only along a single isovolumetric curve in the (T, Conc.) plot. This same equation is applied at higher and lower volumes, and is seen closely to approximate the experimentally determined solubility of quartz over a wide (P, T) range, failing only in regions of high pressure-low temperature and low pressure-high temperature. Solubility curves are extrapolated to 800°C and 2500 bars, the solubility of quartz reaching 1.7 percent by weight at this extreme value.

INTRODUCTION

A theoretical evaluation of the solution process of quartz in supercritical water might be expected to yield three useful results:

(1) An equation could be formulated for the solubility of quartz in water, as a function of temperature and pressure.

(2) Some insight could be gained as to the mechanism by which quartz goes into solution.

(3) The solubility of quartz in water at temperatures and pressures at present unattainable by experiment could be predicted, and the information applied to geologic problems involving the transport of silica in regions of magmatism and hydrothermal vein formation.

The solubility equation will be derived in terms of temperature, specific volume (rather than pressure), and one or more undetermined constants. These latter will be fixed by fitting the theoretical solubility curves to the experimental data of G. C. Kennedy (1950).

DERIVATION OF THE GENERAL FORM OF THE SOLUBILITY EQUATION

The solution of quartz in supercritical water may be represented by a reaction of the form

$$\underset{\text{quartz}}{A(SiO_2)} + B(H_2O) \rightleftarrows D(\text{d}) + E(\text{e}), \tag{1}$$

where d and e refer to two types of unknown particles by which silica is carried in solution. Then at equilibrium,

$$A(\mu_{SiO_2}) + B(\mu_{H_2O}) = D(\mu_d) + E(\mu_e) \tag{2}$$

where μ (the chemical potential)

$$\left.\begin{aligned} &= -3kT\ln(\text{p.f.})^3 + const. \quad (\text{solid quartz}) \\ &= -kT(\ln(\text{p.f.}) - \ln N) + const. \quad (\text{gaseous particles}), \end{aligned}\right\} \tag{3}$$

in which (p.f.) stands for the statistical partition function, N for the number of particles, and k is Boltzmann's constant.

Here the fluid phase is treated as a perfect gas, and the quartz crystal as an Einstein solid. The coefficient 3 appears in the expression for μ_{SiO_2} because, while the Helmholtz free energy of an Einstein solid is a function of the total number of particles in the solid, the differentiation in finding μ from F is with respect to the number of SiO_2 units (1/3 of the number of particles).

A constant term is added to each expression for μ to take account of two constant sources of energy which are neglected in the elementary derivation of the law of mass action:

(1) Zero-point internal energy of the molecule, and

(2) Helmholtz free energy which may be stored in the system by the existence of each dissolved particle, if it is an ion or dipole, by the partial ordering of water dipoles which are within the effective electrostatic field of the dissolved particle.

From (2) and (3) the law of mass action immediately follows:

$$\frac{(N_d)^D (N_e)^E}{(N_{H_2O})^B} = \text{(constant, at fixed temperature and pressure)} = \left[\frac{(\text{p.f.})_d^{\,D}\,(\text{p.f.})_e^{\,E}}{(\text{p.f.})_{SiO_2}^{\,A}\,(\text{p.f.})_{H_2O}^{\,B}}\right] e^{\frac{\text{const.}}{T}} . \tag{4}$$

While the partition functions cannot be evaluated absolutely, their temperature and volume dependences according to classical statistical mechanics are easily determined:

For an Einstein solid, (p.f.) = $(const.)T$
For a polyatomic gas, (p.f.) = the product
$(\text{p.f.})_{\text{Translational}}(\text{p.f.})_{\text{Rotational}}(\text{p.f.})_{\text{Vibrational}}$;

$$\left.\begin{aligned}
(\text{p.f.})_{\text{Trans.}} &= (const.)VT^{\frac{3}{2}} \\
(\text{p.f.})_{\text{Rot.}} &= (const.)T^{\frac{3}{2}} \text{ (non-linear molecule)} \\
(\text{p.f.})_{\text{Rot.}} &= (const.)T \quad \text{(linear molecule)} \\
(\text{p.f.})_{\text{Vib.}} &= (const.)T^{M},
\end{aligned}\right\} \tag{5}$$

Where M = number of normal modes of vibration;
$M = 3P - 6$ (non-linear molecule)
$M = 3P - 5$ (linear molecule)
(P = number of atoms in the molecule). Therefore,

$$\frac{(N_d)^D (N_e)^E}{(N_{H_2O})^B} = \frac{(const.)V^{(D+E)}T^{(const.)}}{V^B T^{(const.)}} e^{\frac{(const.)}{T}} = \frac{(const.)\ T^{(const.)}\ e^{\frac{(const.)}{T}}}{V^{(B-D-E)}} .$$

Since N_s (the number of SiO_2 units in solution) is proportional to N_d, and

N_c is proportional to N_d, and $V \cong N_{H_2O} V_m$ for dilute solutions (V_m = molecular volume of water),

$$\frac{(N_d)^D (N_c)^E}{(N_{H_2O})^B} = \frac{(N_s)^{(D+E)}}{(N_{H_2O})^B} \cong \frac{(const.)\, T^{(const.)}\, e^{\frac{(const.)}{T}}}{(N_{H_2O})^{(B-D-E)}\, V^{(B-D-E)}} ;$$

$$\left[\frac{N_s}{N_{H_2O}}\right]^{(D+E)} \cong \frac{(const.)\, T^{(const.)}\, e^{\frac{(const.)}{T}}}{V_m^{(B-D-E)}} .$$

Finally, since $\frac{N_s}{N_{H_2O}}$ is proportional to the weight percent SiO_2 in solution, denoted by C; and v (specific volume of water) is proportional to V_m,

$$C \cong \frac{aT^J\, e^{\frac{b}{T}}}{v^h} , \qquad (6)$$

where a and b are undetermined constants, J is determined from (5) for any particular solution mechanism, and $h = \frac{B-(D+E)}{D+E}$.

APPLICATION TO EXPERIMENTAL DATA

The volume dependence of the solubility of quartz at 460°C, as determined by Kennedy (1950), is plotted in figure 1. The volume dependence of

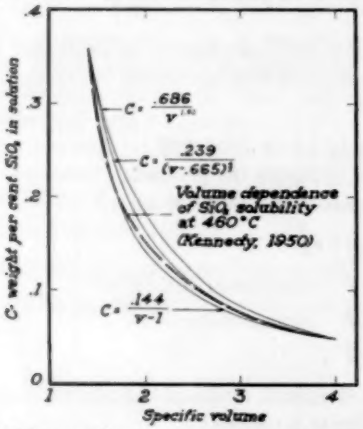

Fig. 1. Quartz solubility isotherms: comparison of several types of theoretical volume dependencies with experiment.

the theoretical solution equation may be tested at this constant temperature, at which (6) becomes

$$C = \frac{(const.)}{v^h} .$$

h and $(const.)$ are fixed by constraining the curve to agree with experiment at two points; $C = \frac{.686}{v^{1.92}}$.

A somewhat better fit is obtained by modifying v to apply to a real gas, as in the van der Waals equation of state, by subtracting a constant term from it, representing a function of the volume of the real gas particles. In the derivation of the translational partition function for a gas, from which the v term arose, this amounts to integration over only as much of phase space as is not occupied by the particles themselves.

In this form, it is seen that the best overall fit is afforded by values of h between $\frac{4}{3}$ and 1. Values within this range will all produce very nearly the same family of solubility curves when the constants in the temperature dependency are fixed.

It is apparent that values of h $\left(= \frac{B-(D+E)}{D+E} \right)$ between $\frac{4}{3}$ and 1 necessarily involve large values of B (the stoichiometric coefficient for H_2O), and consequently complex, hydrated d- and e-particles. The exact nature of the molecules remains indeterminate, since there are many possible ways of constructing these polyatomic molecules, using the stoichiometric coefficient ratios dictated by a particular choice of h. Taking into account what is known of the solution mechanism at low temperatures[1], however, and the fact that silicon always coordinates tetrahedrally with oxygen in solids, the most probable solution mechanisms are:

h	solution process	J	
1	$SiO_2 + 2H_2O \rightleftarrows H_4SiO_4$	3	(7)
$\frac{4}{3}$	$7SiO_2 + 14H_2O \rightleftarrows (H_4SiO_4)_2 + 5H_4SiO_4$	4	(8)

Here J, the exponent of T in the numerator, has been determined from equations (5). These two values of J lead to almost identical families of curves.

Assuming reaction (8) to represent the solution mechanism, and correcting the volume term by the constant amount determined by fitting to the experimental curve in figure 1,

$$C = \frac{aT^4 \, e^{\frac{b}{T}}}{(v-.665)} \, .$$

The two undetermined constants are fixed by constraining the 600 bar

[1] Freezing-point lowering experiments show that silica dissolves predominantly in the form of a monosilicic acid, probably H_4SiO_4 (Krauskopf, 1956; White, Brannock and Murata, 1956; Weitz, Franck and Schuchard, 1950; Alexander, Heston and Iler, 1954). It has been shown (Weitz, Franck and Schuchard, 1950) that silica in solution occurs in disilicic and higher polysilicic acids in addition to the monosilicic acid molecule, the equilibrium proportions depending on the temperature and pH (all of these experiments were carried out at atmospheric pressure). The degree of polymerization may be determined by the higher average molecular weight found by the freezing point method, and by the colorimetric silicomolybdate reaction.

isobaric solubility curve to agree with experiment at two points (420° and 550°C). The equation then becomes

$$C = \frac{(1.13 \times 10^{-11})\ T^4}{e^{\frac{1942}{T}}(v-.665)^{\frac{4}{3}}} \quad . \tag{9}$$

This family of curves is superimposed on Kennedy's experimental curves in figure 2, and extrapolated to higher temperatures and pressures in figures 2 and 3.

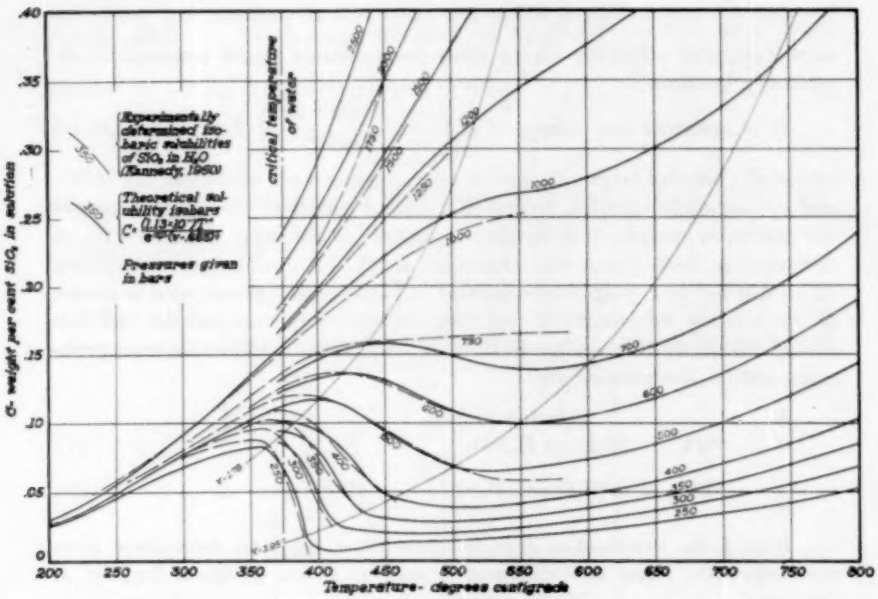
C- weight per cent SiO2 in solution
Temperature- degrees centigrade
critical temperature of water
Experimentally determined isobaric solubilities of SiO2 in H2O (Kennedy, 1950)
Theoretical solubility isobars
Pressures given in bars

Fig. 2. Experimental and theoretical solubility of quartz as a function of temperature and pressure.

DISCUSSION OF ASSUMPTIONS AND VALIDITY

(1) Treatment of the fluid phase as a perfect gas: An attempt to treat the fluid phase by rigorous methods of statistical mechanics as a real gas would greatly increase the complexity of the solution equation. As was noted above, the assumption of a perfect gas was modified to the extent of subtracting a constant amount from the volume term. The amount (within limits) or non-existance of this constant does not profoundly alter the solubility curves. Particle interaction was also partially accounted for by introducing an $e^{\frac{(const.)}{T}}$ term, which contains the ordering effect of charged or dipole solution particles on the neighboring water dipoles.

(2) Treatment of quartz as an Einstein solid; neglect of the high-low quartz inversion point: The Gibbs free energy of quartz, as a function of temperature, has been measured calorimetrically (Mosesman and Pitzer, 1941).

This experimental curve can be very closely fitted over the temperature range 300°–1000°A by an equation of the Einstein solid form,

$$\mu = -9kT\ln(const.)T + const.,$$

by fixing the two constants. The high-low quartz inversion point (846°A or higher, depending on pressure) introduces no divergence in the curves.

(3) Assumption of a single solution mechanism over the entire (P,T) range: Obviously, this is not true; decreasing volume will cause the solution molecules to associate (polymerize). For example, if the adopted mechanism of solution into partially polymerized H_4SiO_4 molecules is correct, then the experimental volume-concentration curve in figure 1 could be perfectly matched by the following mechanism:

Specific volume	Pressure at 460°C	Form in which SiO_2 exists in solution
<1.42	>1700 bars	$(H_4SiO_4)_3$ (trimer) and/or higher polymers
1.42	~ 1700 bars	100% $(H_4SiO_4)_3$ (trimer)
1.52	~ 1300 bars	100% $(H_4SiO_4)_2$ (dimer)
2.025	$\sim$ 700 bars	100% (H_4SiO_4) (monomer)
>2.025	$<$ 700 bars	(H_4SiO_4) (monomer) and/or simpler ions or molecules

For values of v between those tabulated, the solution process will of course involve both of the two corresponding processes.

This differing solution process causes wide fluctuations in J, the exponent to which T is raised in the numerator. J becomes 15 or greater at the lowest volumes considered, and .1 or less at large volumes. It can be seen then, that the solution model would be strictly applicable only along the $(v = 1.78)$ isovolumertic curve (plotted on figs. 2 and 3), this being the volume corresponding to the ratio of monomer to dimer in (8). But since the two undetermined constants a and b were fixed at two volumes $(v = 1.783, 3.95)$, the solution equation becomes less accurate at $v = 1.78$, but equally applicable over the range of volume 1.783 – 3.95. The degree of accuracy achieved can be judged by comparing the plotted theoretical and experimental curves in figure 2.

The degree of error introduced into the theoretical curves by the assumption of one model is also seen in figure 2. At very high values of v, the solution process involves simple particles (probably ions), J becomes small, and the second derivative (curvature) of the curve decreases. This can be seen in the departure of the 500 bar experimental curve from theory at temperatures greater than 500°C. At low values of v, the solution process involves high polymers, J becomes large, and the second derivative of the curve increases (note the 1750 bar experimental curve). The extrapolations to high temperatures and pressures in figure 3, however, fall within a narrow range of volume, and should be very nearly correct.

APPLICATION TO NATURAL SOLUTIONS

In figures 2 and 3, solubility isobars have been extended to 800°C and 2500 bars. The P-v-T data of water used are those of Kennedy (1950a). The isobars can be further extended to any (supercritical) point where the P-v-T

behavior of water is known or can be predicted. Agreement with experiment holds surprisingly well in the subcritical region also (fig. 2); however, at temperatures below 100°C and at low pressure, large discrepancies appear.

Using figures 2 and 3, the solubility of quartz in pure water in geologically realizable situations in the upper part of the earth's crust can be predicted with some accuracy. Care must be exercised in assuming that the water in question did not contain components which are known to enhance the solubility of quartz in water, particularly the alkali metals. Friedman (1951) found that at 300°C and atmospheric pressure, a solution containing 2 percent by weight Na_2O will dissolve 4 percent SiO_2; a 10 percent Na_2O solution dissolves 30 percent SiO_2.

These alkaline solutions undoubtedly react with quartz and water to form new types of molecules having higher solubilities than the SiO_2—H_2O mole-

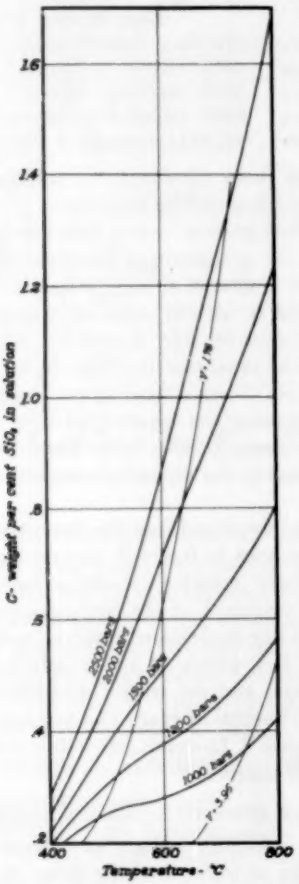

Fig. 3. Theoretical solubility of quartz, at higher pressures.

cules. It is not to be expected that the solution equation derived for quartz in pure water would be applicable to them.

Neither would solubility of amorphous silica (SiO_2 glass) be predicted by the derived equation. Actually, the "solubility" of SiO_2 glass is not meaningful. Since the glass is metastable over the range of (P,T) considered, it will always tend to go into solution to a greater extent than quartz; consequently, SiO_2 glass brought into contact with supercritical water would dissolve (into the same type of molecules as would crystalline quartz) until the solution were supersaturated with respect to crystalline quartz. Thereafter, quartz would crystallize, and glass would continue to dissolve, until at equilibrium, the system would contain only quartz and a saturated aqueous solution of SiO_2.

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ULTRAVIOLET-ABSORBING COMPONENTS OF FOSSIL AND MODERN PLANTS IN RELATION TO THERMAL ALTERATION OF LIGNINS

S. M. SIEGEL, B. LeFEVRE, Jr. and R. BORCHARDT

ABSTRACT. It is shown that fossilized vascular cryptogamic plants have far fewer ultraviolet-absorbing components extractable by means of various organic or aqueous solvents than related living modern forms. In an effort to account for the loss of aromatic components, assumed to be principally lignin-like in character, lignin and sawdust were exposed to temperatures of 100-230° C in air or under nitrogen and changes in properties compared. Changes included overall losses in ultraviolet absorption, shifting, and finally, disappearance of characteristic absorption peaks, and loss in solubility. The latter may be attributed to cross-linking of lignins to form an insoluble polymer of high molecular weight. Preliminary study of the kinetics of thermal alteration show that each temperature has a characteristic asymptotic value for insolubilization of lignin suggesting the possible utility of this substance as an indicator of the local thermal history in regions containing fossilized vascular plant remains. Survival of lignins in identifiable, soluble form was favored by lower temperatures, the absence of oxygen, and association with normal cell wall constituents of woody tissues.

INTRODUCTION

Among biochemical substances, the lignins are recognized as an exceptionally stable group of aromatic polymers. (Gortner, 1949). Nevertheless, lignins are known to undergo degradation with loss of methoxyl content during the process of fossilization (Manskaya, 1954). As one aspect of a study of changes in biochemical substances during experimentally simulated fossilization, fossilized vascular plant tissues were examined for lignin, and it was noted that with respect to the amount of ultraviolet absorption and appearance of distinctive absorption maxima, fossilized specimens were far poorer than related modern specimens. Assuming the lignins and related substances to be mainly responsible for ultraviolet absorption, demethylation would not suffice to destroy the aromatic character of extracts from fossilized material, hence another explanation for the loss or absence of distinctive ultraviolet absorption in fossilized lignin-containing tissue must be sought. This communication presents evidence that these changes are in part, at least, a consequence of thermal alteration of the lignin molecule.

PROPERTIES OF FOSSIL AND MODERN PLANT EXTRACTS

It is not intended that an examination be made here of evolutionary relationships or comparative biochemistry, thus a general discussion of differences in specimens studied will be minimal. The principal materials used in this study were the Pennsylvanian forms *Lepidodendron* and *Calamites*, together with living *Selaginella rupestris* and *Equisetum arvense*. Other fossil forms included *Annularia* (Pennsylvanian), *Equisetum columneus* (Triassic), and *Salix elongata* (Miocene tertiary); living forms included *Psilotum triquetrum* and *Salix nigra*.

Approximately 5 gm samples of fossil specimens (<5 mm size) were extracted with 20 ml of specified solvent (table 1) for 30 minutes on a boiling water bath, extracts centrifuged free of colloidal matter at 2×10^4 g and appropriate dilutions analysed in the Beckman model DUSpectrophotometer over the range 220-350 mu.

Modern plant material was handled similarly, save that samples of 100-500 mg weight were used.

Representative data (table 1) show the relative paucity of ultraviolet-absorbing components in two pairs of related modern and fossil forms. It should be pointed out that several fossil extracts in aqueous solvents exhibited strong ultraviolet absorption at 335 mu with curves similar to those obtained when samples of shale, granite, hornblende, and gold-bearing milky quartz were extracted with the same solvents. As this spectral type remained unchanged after repeated ignition with oxidants, these were concluded to be attributable entirely to inorganic substances and discounted in table 1.

TABLE 1

Ultraviolet Absorption by Extracts of Fossil and Modern Plant Forms

	Lycopsida						Sphenopsida					
	Selaginella			Lepidodendron			Equisetum			Calamites		
Solvent	Max[a]	Min[b]	R[c]	Max	Min	R	Max	Min	R	Max	Min	R
HCl (36%)	280	250	1.58	None	—	—	280	240	2.14	None	—	—
HCl-Ethanol (1:1)	277 332	250 310	1.32 1.10	None	—	—	285	250	2.64	None	—	—
KOH (5%)	272	265	1.03	None	—	—	275	250	1.30	None	—	—
KOH-Ethanol (5%)	260-270 Shoulder			None	—	—	275	260	1.10	None	—	—
Methanol	266 340	250 300	1.16 1.22	270	250	1.13	270	250	1.27	None	—	—
Ethanol	270 340	250 310	1.16 1.18	240	220	1.37	270	260	1.17	252	245	1.03
Dioxane	265	250	1.06	275	250	1.31	280 315	260 300	1.16 1.02	255	245	1.04
Chloroform	275	260	1.15	None	—	—	275	265	1.07	None	—	—

[a] Wave length at which maximum absorbancy occurs

[b] Wave length of lowest absorption above 220 mμ

[c] Ratio of absorbancies at maximum and minimum wave lengths

In general, lignins are of limited solubility in neutral solvents. Highly polar compounds, methanol for example, do not dissolve lignins save for the ethanol solubility of the so-called protolignins of younger tissues which have not yet been fully transformed. Equally unsuitable are the hydrocarbon and halogenated hydrocarbon solvents including hexane and chloroform. Thus, aromatic substances appearing in the above solvents are presumed to be simpler phenolic compounds, including, in the case of fossil plants, possible lignin degradation products. Conspicuous among lignin solvents is dioxane, although it has been questioned (Brauns, 1952) whether or not this substance is actually effective when neutral. Spectra of the dioxane fractions (fig. 1) are all of the common aromatic type, but differ in exact form. Further the *Calamites* spectrum differs from the typical lignin forms (shown by *Lepidodendron* and *Equisetum* and the Selaginella absorption curve is itself atypical.

Some aromatic compounds related to lignins (DeStevens and Nord, 1953) possess the benzopyrone oxygen bridge from side chain to ring, hence

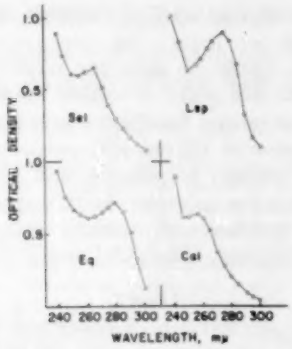

Fig. 1. Ultraviolet Absorption by Dioxane extracts of *Selaginella* (sel), *Lepidodendron* (Lep), *Equisetum* (Eq), and *Calamites* (Cal).

are capable of forming oxonium salts with mineral acids and can often be dissolved in strong HCl. Such substances may account for the HCl-soluble materials found extracts of modern plant specimens.

Solutions of strongly dissociated alkaline substances can dissolve the weakly acidic phenols by formation of phenoxide (phenate) salts. Thus both aqueous and ethanolic KOH have been used as solvents for the more refractory polymeric aromatic substances such as lignin. Spectra in KOH are of the typical aromatic form, but are confined to the modern plant specimens.

Finally, ethanol-HCl solubilizes polymeric aromatic compounds by rendering them more polar through H-ion catalyzed ethanolysis. Higher molecular weight lignins unaffected by all neutral solvents may be rendered soluble by treatment with this substance. Again the typical lignin spectra are evident only in modern forms.

In evaluating spectral data, curves with maxima in the 265-285 mμ region are ascribed to the phenoxy group C_6H_5-O- of lignins, tannins, etc.; the 315-340 peak is indicative of conjugated phenoxy group-side chain systems (DeStevens and Nord, 1953); and maxima in the region of 255 mμ and below may be attributable to simple aromatic hydrocarbons or partially hydrogenated derivatives thereof. Note that the fossil forms contain the last mentioned group but lack the components absorbing beyond 300 mμ. Using 2, 4-Dinitrophenylhydrazine (Shriner and Fuson, 1948), the aldehydic or ketonic carbonyl group was detected in the methanol and ethanol extracts of both fossil forms. The phloroglucinol color reagent for lignin gave positive results with dioxane extract of *Calamites* and KOH and KOH-ethanol extracts of *Lepidodendron*.

THERMAL TREATMENT OF LIGNIN AND WOOD

A soft, grey-brown, waxy substance isolated from *Lepidodendron* corresponds in composition and properties to a hydrogenated polymeric substance of the lignin type (C 60.5%, H 8.2%, compound with C 60-65%, H5-6% for lignins) and exhibits only weak absorption in the near ultraviolet, suggesting

saturation of aromatic nuclei as one means of abolishing strong ultraviolet absorption. The main factor proposed here, however, in loss of aromatic properties is indicated in figure 2. Indulin, a commercial pine lignin isolate was given brief exposure to elevated temperatures while under nitrogen. After treatment, the samples were dissolved in dioxane and this solution diluted 1:100

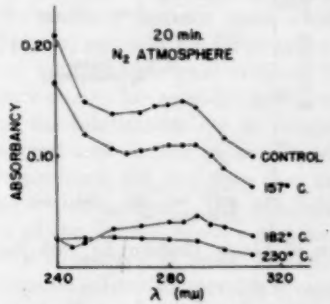

Fig. 2. Changes in the Spectral Characteristics of Lignin (Indulin A) after Treatment at Various Elevated Temperatures in Nitrogen Atmosphere.

with ethanol for spectral analysis. The control and 157° samples have typical lignin spectra with the latter peak shifted from 285 mu to 290 mu. Exposure to higher temperatures results in a large drop in absorbancy together with loss of a distinctive peak. Pine sawdust treated in a similar fashion exhibited far less change; thus for control, 157°, 182° and 230° treatments respectively, the relative absorbancy at 285 mu was 100, 75, 31, 16 for Indulin, but 100, 100, 50, and 43 for sawdust. Sawdust heated in air gave for the same treatment relative absorbancies of 100 (control), 86, 49, and 29, showing a more rapid fall-off than under nitrogen. Employing milder treatment temperature for a longer time (table 2), it is clear that a regular shift in spectral peak accompanies changes in absorbancy. Here absorbancy is expressed as $E\frac{1\%}{1_{CM}}$ value, or absorbancy by a 1 percent solution whose thickness (light path) is 1 cm. Considering these data as they may apply to natural conditions, two factors contributing to the survival of lignin would be (a) depth of burial or submergence as a determinant of oxygen concentration, and (b) amount of residual cell-wall polysaccharide, as this may protect lignin itself from decomposition. In a recent study (Zhuravleva, 1954), it has been demonstrated that top peat which is high in bitumen content is low in humic acid and lignin whereas the opposite relationship holds for composition of bottom peats. Lignins might also be protected by blockage of the oxidation-sensitive aromatic OH group; that lignin exists in part in glycosidic form in the cell wall has also been established recently (Kawamura and Higuchi, 1954; and Traynard and Ayoud, 1954).

As temperature treatments became more severe, it was observed that, after transfer of samples to dioxane, a progressively larger residue remained undissolved. Examination of insolubilization of indulin as a function of tem-

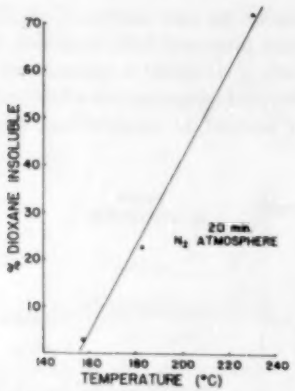

Fig. 3. Insolubilization of Lignin (Indulin A) with Increasing Temperatures in Nitrogen Atmosphere.

TABLE 2

Change in Absorption Characteristics of Indulin at 100°C

Time (hours)	λ_{max}	$E^{1\%}_{1\,cm}$
0	280	214
40	280	230
125	290	236
175	290	184
250	310	44

perature revealed a linear increase with increasing temperature of sufficient magnitude (72 percent insoluble after 20 minutes at 230°) to account for most of the loss of absorbancy in treated samples (fig. 3). The dioxane insoluble residues, when permitted to remain in this solvent, underwent swelling to several times the original volume, suggesting that cross-linking of lignin molecules into a higher, insoluble polymer may occur. Interestingly, it was noted that at various temperatures a characteristic asymptotic value for insolubilization was attained with respect to time. For example, at 182°, the asymptote for indulin was attained after somewhat more than 20 minutes and corresponded to 40-50 percent insoluble. At 100°C, the asymptote was obtained after 250 hours' treatment and corresponded to a limiting value of about 15 percent dioxane-insoluble lignin.

One plausible explanation for the behavior of lignin upon pyrolysis may be that the overall phenomenon of insolubilization consists, in fact, of a series of reactions, each corresponding to cleavage of a particular bond, each cleavage characterized by a particular heat of activation. The dissociation energies for homolytic cleavage of carbon-to-carbon bonds (Steacie, 1954) would permit decomposition of benzoyl groups into phenyl radicals and other products (27.5 kcal/mole) under conditions not affecting dissociation of toluene into phenyl and methyl radicals (89 keal/mole). The pyrolysis of a

lignin model substance, anisole, $C_6H_5OCH_3$, yields, as primary products, methyl, phenyl, and phenoxy radicals; benzaldehyde yields, overall, benzene, carbon monoxide, and diphenyl. Pyrolysis of propyl benzene and toluene both lead to formation of dibenzyl (1, 2-diphenylethane). When lignins are subjected to thermal decomposition, one of the volatile products formed is methanol (Brauns, 1952) whose origin may be explained most easily by assuming cleavage of the methoxy benzene units which characterize the substance into CH_3O and phenyl radicals, the former then abstracting a hydrogen atom to form methanol and an additional radical. Thus reactive sites could remain in lignin polymer chains for cross-linking termination reactions.

If the kinetics of insolubilization are as temperature-specific as these preliminary studies suggest and remain so over a wide range of conditions including variations in pressure, pH, etc., then they may well find application eventually as a geologic thermometer. The feasibility of such a chemical change as an indicator of the thermal history of a localized area can only be assessed after extensive experimental work and field observation, but in principle the ratio of organic solvent extractable aromatic substance in a fossil to its total carbon (principally aromatic residues) as determined by combustion should be an approximate measure of the residual solubility of lignin, hence of the highest temperature to which fossilized plant materials have been subjected.

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NEW STRATIGRAPHIC NAMES FOR EARLY PLEISTOCENE DEPOSITS IN SOUTHWESTERN KANSAS

CLAUDE W. HIBBARD

ABSTRACT. At a Pleistocene conference held in Lawrence, Kansas on June 28-29, 1956, it was agreed that for the present a two-fold classification of stratigraphic units would be used in Kansas. The following new names as applied to Pleistocene units are defined: Meade group, Ballard formation, Angell and Atwater members and Sanborn group.

A Pleistocene conference was held in Lawrence, Kansas on June 28-29, 1956, at the invitation of Frank C. Foley, Director of the Kansas State Geological Survey. The purpose was to discuss certain disagreements in correlation and in stratigraphic nomenclature. In attendance were members of the State Geological Surveys of Kansas, Nebraska, and Oklahoma, the United States Geological Survey and Claude W. Hibbard of the University of Michigan.

The group agreed that for the present a two-fold classification would be used in Kansas, one classification for southwestern Kansas and another for the remainder of the state, with the exception of the southeastern corner. The revised classification summarized in this paper is to be used in southwestern Kansas. It is probably applicable also in northwestern Oklahoma, but not elsewhere in Kansas. The new agreement on some correlations and principles of nomenclature necessitated changes in the stratigraphic classifications of the Kansas State Geological Survey and of Claude W. Hibbard. A special committee was therefore formed to meet in southwestern Kansas and to review the stratigraphic sequence and select new rock names and type localities. The committee consisted of the Directors of the Kansas, Nebraska and Oklahoma Geological Surveys—F. C. Foley, E. C. Reed, and Carl C. Branson respectively; C. W. Hibbard, University of Michigan; C. K. Bayne and Ada Swineford, Kansas Geological Survey; and S. W. Lohman, T. G. McLaughlin, and A. R. Leonard, United States Geological Survey. The members of the committee, except E. C. Reed, spent July 24 and 25 in Meade and Seward counties, Kansas, examining Cenozoic outcrops.

A later publication of the State Geological Survey of Kansas will revise the Pleistocene stratigraphic classification for the remainder of Kansas. Dr. Frank C. Foley, Director of the Kansas Survey wrote as follows on April 20, 1957: "Since the conference on Pleistocene stratigraphic nomenclature held in Lawrence, Kansas June 28 and 29, 1956, and the field conference in Meade County on July 24 and 25, 1956, it has not been possible as of April, 1957, for the State Geological Survey of Kansas to select names to replace Meade and Blanco as formation names in the stratigraphic column to be used in Kansas other than in the Meade County area. It is hoped that selection of the necessary new names can be accomplished in the near future. When the names are selected it is planned to publish them and so to complete the tentative dual classification."

The accompanying chart (fig. 1) summarizes the new classification adopted for southwestern Kansas by the Lawrence Pleistocene Conference,

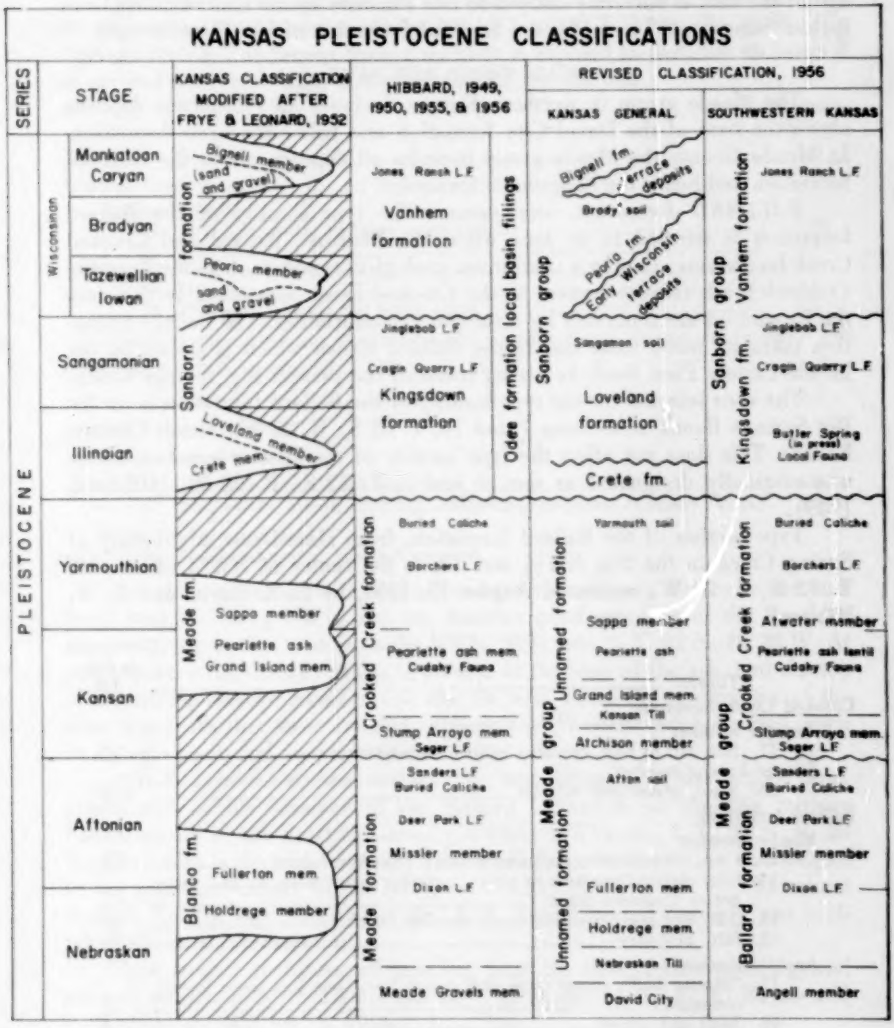

Fig. 1.

and the changes from the former Kansas Survey classification and that of Claude W. Hibbard (1949).

The Rexroad formation was included in the Blanco formation of the former State Geological Survey of Kansas classification. The position of the Rexroad formation was discussed at the Pleistocene conference but decision on it was deferred. It is now recognized as older than the Meade group. The

age of the unit is currently carried as late Pliocene by the United States Geological Survey and I consider the Rexroad formation of late Pliocene age.

MEADE GROUP, NEW NAME

The Meade group in northern Kansas, includes all Pleistocene deposits above the base of the David City formation and below the Crete formation. In Meade County the Meade group includes all deposits above the Rexroad formation and below the Kingsdown formation.

BALLARD formation, new name.—The type locality of the Ballard formation is selected in an area where the Rexroad, Ballard and Crooked Creek formations occur in a continuous geological exposure, with the Pearlette (volcanic) ash (lentil) present in the Crooked Creek formation. In this area the formations are separated by erosional unconformities. The Ballard formation takes its name from the Louise Ballard Ranch which is shown on the Meade County Platt Book as having included the present Big Springs Ranch.

The area selected for the type locality of the Ballard formation is on the Big Springs Ranch in sections 7 and 18, T. 32 S., R. 28 W., Meade County, Kansas. This does not affect the type locality of the Missler member, which was originally designated as secs. 6 and 7, T. 32 S., R. 28 W. (Hibbard, 1949).

Type section of the Ballard formation, from Hart Draw, a tributary of Spring Creek in the S½ NW¼ sec. 18, to the center of NW¼ of sec. 18, T. 32 S., R. 28 W., measured August 15, 1956, by C. K. Bayne and C. W. Hibbard.

	Thickness in feet
Topsoil	1.0
Crooked Creek formation	
Atwater member	
17. Silt, tan to buff, contains caliche nodules near top	7.5
Stump Arroyo member	
16. Sand, gravel and cobbles	17.0
Ballard formation	
Missler member	
15. Clay, silty, brown, mollusks present (Sanders fauna)	1.5
14. Silt, clayey (weathers to gray), contains many mollusks and vertebrates (Sanders fauna)	1.6
13. Silt, buff-gray, contains much nodular caliche	1.0
12. Silt, buff-gray	8.0
Angell member	
11. "Mortar bed" (limey sand and gravel lower one foot more loosely cemented)	1.8
10. Sand and gravel	5.5
Rexroad formation	
9. Clay, reddish gray, contains mollusks	3.0
8. Caliche	0.5
7. Sand, fine and medium	2.0
6. Caliche	0.2
5. Silt, sandy, light reddish gray mottled yellowish tan	4.3
4. Caliche, hard and massive	0.5
3. Silt, light gray, containing many mollusks (Rexroad fauna)	2.5
2. Silt, reddish gray, containing some fine sand	2.0
1. Silt, light reddish gray, containing many caliche nodules	7.5
Bed of Hart Draw, from base of cut upward	

The section was continued on the east side of the next draw to the west in approximately the center of the NW¼ sec. 18, T. 32 S., R. 28 W., Big Springs Ranch. The Stump Arroyo member is exposed in part, but an interval is covered with slope wash and vegetation on the east side.

	Thickness in feet
Topsoil	1.0
Crooked Creek formation	
Atwater member	
22. Silt, gray-white, contains much caliche	1.75
21. Silt, gray	5.5
20. Clay, reddish brown	1.0
19. Silt, gray	4.5
18. Pearlette volcanic ash lentil, clean	1.0

Section measured on the west side of this draw, in approximately the center of the NW¼ sec. 18, T. 32 S., R. 28 W.

Topsoil	0.5
Crooked Creek formation	
Atwater member	
18. Pearlette volcanic ash lentil	6.0
17. Silt, sandy, yellow mottling, containing mollusks (Cudahy fauna)	2.5
Stump Arroyo member	
16. Sand and gravel, base not exposed	

A much thicker deposit of the Pearlette volcanic ash occurs in the next draw west in NW¼ NW¼ sec. 18. Another good exposure of the Pearlette ash occurring in this area is in the NW¼ SE¼ sec. 7, T. 32 S., R. 28 W. At this exposure the Cudahy fauna is present at the base of the ash, and the top of the Stump Arroyo member can also be seen. From the topography of the area it appears that these isolated exposures of Pearlette ash were laid down in a single basin and were continuous.

ANGELL member, new name.—The best exposure of the Angell sand, gravel and cobble member of the Ballard formation on the Big Springs Ranch occurs in the Sanders Gravel pit, SE¼ NW¼ sec. 7, T. 32 S., R. 28 W. The name is derived from the old Angell Schoolhouse which was located in the southeast corner of the NE¼ sec. 31, T. 32 S., R. 29 W. The school district, No. 15, was named after Mr. A. V. Angell, one of the early and leading citizens of that community.

Type section of the Angell member, from the base of the Sanders gravel pit and measured northeast toward U. S. Highway 54, by C. K. Bayne and C. W. Hibbard, August 15, 1956.

Crooked Creek formation	
Stump Arroyo member, sand gravel and cobbles	
Ballard formation	
Missler member	
5. Clay, reddish brown, limy	0.7
4. Silt, reddish gray, some nodular caliche	9.1
3. Caliche	1.8
2. Silt, tan-gray, containing caliche nodules	13.3

Angell member

1. Sand, gravel and cobbles, cross bedded at base and cemented in part 13.7

Rexroad formation at base.

A good exposure of the cemented Angell member can be seen in the northwest corner of the NE¼ sec. 24, T. 32 S., R. 29 W., along the south bank of Spring Creek, which is approximately one mile southwest of the type locality. At this locality the Rexroad formation is exposed and contains both vertebrate and invertebrate fossils.

ATWATER member, new name.—Type section of the Atwater member of the Crooked Creek formation is in the N½ sec. 21, T. 33 S., R. 28 W., on the east side of Crooked Creek, Meade County, Kansas. The member consists of sandy silt, silt, silty clay, and clay which contains the Pearlette ash lentil, when present; also a massive caliche is generally present at the top of the member. This member overlies the Stump Arroyo sand and gravel member. The name is derived from the old Atwater Post Office which was first located in the center of the S½ SE¼ sec. 34, T. 33 S., R. 29 W., and later moved to the SE¼ sec. 21, T. 34 S., R. 29 W. The following stratigraphic section at the type locality is modified after Frye, 1942, p. 71.

Topsoil Crooked Creek formation Atwater member	Thickness in feet
9. Silt, sand and some clay, tan to buff brown, contains some caliche nodules. The surface at the top of the bluff is covered with a rubble of caliche	14.8
8. Silt, sandy, gray to tan	5.4
7. Clay, with some silt and sand, light gray, massive. Breaks with a conchoidal fracture when dry (Borchers fauna at base)	4.5
6. Silt, clay, and some sand, gray, massive, containing a few calcareous nodules (Borchers fauna at top)	6.4
5. Pearlette volcanic ash, pearl gray, lenticular, somewhat impure	3.1
4. Clay, silt, and some sand, tan gray, and brown gray, massive, (Cudahy fauna occurs in top 12 inches and base of ash)	9.5
3. Silt, red brown to reddish, containing caliche nodules	6.0
Stump Arroyo member	
2. Sand, coarse gravel and some silt, brown	2.8
1. Sand, coarse, reddish to light tan, and well sorted, containing white quartz pebbles, grading upward into finer more poorly sorted sand, and gravel at top	10.1
Ogallala formation	

SANBORN GROUP, NEW NAME

The Sanborn group in southwestern Kansas includes the Kingsdown and Vanhem formations, as well as the isolated basin fillings termed the Odee formation (Hibbard, 1949).

The committee is most grateful to the many landowners of Meade and Seward counties, Kansas, who gave us free access to their ranches to examine

geological exposures; also, to many residents who made available the early records and maps which were used in the selection of the new names here proposed. We wish to thank George V. Cohee, Chairman, Geologic Names Committee of the United States Geological Survey, for confirming the availability of the new names. I am indebted to Frank C. Foley and Charles K. Bayne for reading the manuscript and offering valuable suggestions.

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ESSAY REVIEW

Philosophy of Science; by PHILIPP FRANK. P. xxii, 394. New York, 1957 (Prentice-Hall, $7.65).—The first fourteen chapters of this book give a stimulating account of the historical and philosophical environment in which western science has grown and shaped its institutions. To begin his task, the author distinguishes pure science from that which is proper to philosophy, and sympathetically portrays the 16th Century Aristotelian who saw the medieval world as an organic whole in which scientific and philosophical truths formed a natural partnership. In many ways the breakdown of this partnership at about 1600 A.D. has influenced the character of our present scientific culture. In particular, modern science (especially advanced theoretical physics) abandons common sense catagories in favor of abstractions which tend to be unintelligible in a Thomistic sense. The willingness of scientists to put aside common sense, and hence to proceed without the benefit of philosophical insight, says Frank, signaled the parting of philosophy and science; for the scientist now fixes his own demands and criteria of truth. The breakdown is traced from its origin in the Copernican revolution to the 20th Century. As a prominent physicist who has given long and thoughtful attention to the philosophy of science, Frank provides many cogent and authoritative examples of the problems which beset modern physics and common sense philosophy in six chapters devoted to the relativity and quantum theories and their interpretations.

A further critique of the ideas of casual law, scientific induction, probability, and the validation of scientific theories leads Frank to his central thesis* in Chapter 15. We learn first that physical theories of high generality cannot be uniquely chosen on the basis of their formal correctness plus their agreement with experiment. If from the class of all theories which meet these two established criteria a further selection is to be made, then, Frank argues, sociological and psychological criteria should be consulted. These areas constitute the pragmatics of scientific method. We learn that in fact, certain identifiable pragmatic-sociological criteria have long been determining influences in the choice of a theory when a crisis develops in physics. For instance, the preference for a Copernican universe was based on its great mathematical simplicity and ultimately, its fitness to further generalization in the hands of Newton. Similarly, opposition to Copernicus was based on its incompatibility with the common sense catagories of Aristotelian Europe. However, criteria such as simplicity, fitness to further generalization and common sense are philosophical rather than scientific. Frank's thesis is that such criteria are quite acceptable (providing formal and empirical criteria are first satisfied), and he suggests that the situation in modern physics permits one to believe that science and common sense philosophy may affect a genuine reunion on this basis. For instance, the author describes Bohr's complementarity as "a decision to integrate all possible analogies with common sense experience into one world picture." The classical catagories of casuality, particle motion, and wave motion are all preserved in modern physics; but they are separately incomplete, for no single description is adequate by itself to repre-

* See also Frank, P., 1954, The reasons for the acceptance of scientific theories: Scientific Monthly, vol. 79, p. 139.

sent quantum mechanics. Therefore, common sense rules that all descriptions be employed interchangeably as a shopman selects different tools according to the task he is to perform. It is to be remembered that Frank stresses the pragmatic nature of extra-scientific choice, and that causality, particle and wave motion are considered only as common sense analogies.

The book goes further in its last chapter toward accepting sociological criteria in order to determine a choice of scientific theory. We are told "If we add requirements of simplicity and agreement with common sense, the determination becomes narrower, but it does not become unique. We can still require their fitness to support desirable moral and political doctrines. All these requirements together enter into the determination of a scientific theory." Again Frank established that scientific belief does in fact have moral and political repercussions. So long as this is so, he argues, the scientist may use his liberty to choose among theoretical alternatives in such a way as to support desirable moral and political ends. We can follow this advice without relaxing the usual scientific demands on a theory, we know historically that scientific belief is effective in its support of moral and political doctrines, and as human beings we are furthermore interested in the course of moral and political affairs. So, why not? Again, the rule is pragmatic and sociologically experimental. If scientific technology can support the material demands of society without compunction, then theoretical science can just as well support its moral and political needs. In this way, Frank completes the cycle to a new Aristotelian society wherein science and common sense philosophy once more have a common ground in the social order.

The reviewer would like to advance a criticism on the criteria of common sense description, and the fitness of a theory to support moral and political aims. Unquestionably formal completeness and empirical verifiability do not lead to unique theoretical concepts in advanced physical theory. To some extent, we are free to require formal simplicity, conceptual elegance, and the fitness of a theory to further generalization. However, it is difficult to see how a common sense requirement can be used to select between two contending theories neither of which is isomorphic with common sense language. In each case, we would have to select a fragment of the common sense language and match it with a fragment of the formal theoretical language. Perhaps the criterian should refer to the number of fragmentations that are necessary, and require that that number be minimized. In any case, the syntax of the common sense language would be in the large destroyed, and hence too its supposed value for philosophy. We are given the impression that quantum mechanics has somehow taught us to use a common sense criterion (viz: reference to Bohr's complementarity principle); but although quantum mechanics may lead one to feel the need for such a description, that theory was not selected from among others because of its agreement with common sense. Frank does not clarify how this criterion is to work in a given case. All historical examples which are discussed dramatize the movement away from common sense choice without showing in what sense physics might profitably move toward it. The most unconvincing part of Frank's suggestion lies in the fact that he devotes so much of his book to a criticism of past and present

common sense judgments without attempting to show how they have been, or could be advantageously employed where there is an actual choice.

Again the criterion of 'fitness of a theory to support moral and political aims' is vaguely presented amid examples of how this criterion has been abused. We are tempted to ask how Frank would apply the criterion in a given case. For instance, between Whitehead's relativity and Einstein's relativity, should an American committed to western democratic precepts and Judaic-Christian morality offer a judgment on Einstein and Whitehead consistent with his commitment? If so, how is it decided which theory should be endorsed. Frank does not himself offer any such judgments, and it becomes increasingly clear that he would not do so. On page 355 he states "If a theory built up exclusively because of its agreement with observed facts told the 'truth' about the world, it would be foolish to assume seriously that the acceptance of a scientific theory should be influenced by reasons of simplicity and agreement with common sense, let along moral, religious, or political grounds. However, we have learned that 'agreement with observed facts' never singles out one individual theory. . . . If we consider this point, it is obvious that such a . . . theory cannot be 'The Truth'. . . . A theory is now rather regarded as an instrument that serves some definite purpose." For Frank, the touchstone of ontological truth is still that which is empirical. He never really chooses where there is a non-empirical choice, and he criticizes Margenau at one point for believing in the reality of probabilities even though he (Margenau) well knows that this reality cannot be directly apprehended. We cannot expect, therefore, that Frank is likely to commit himself to the desirability of a genuine theoretical choice except as others accept it (i.e.: believe in its truth) and allow it to influence their moral and political judgments. The program which Frank proposes begins to sound like a deception. It lacks his own firmness in dealing with such absurdities as would follow if we were all convinced by him that our concept of truth is not a judge of our choice.

The reviewer hopes that his criticism of these two points does not obscure his main impression of the book. The last chapter does raise more questions than it answers, but the first fourteen are highly recommended for their clarity, richness, and analysis of matters which are rarely given sufficient attention by scientists. R. MOULD

Laboratory Manual of Crystallography for Students of Mineralogy and Geology; by GEORGE TUNNELL and JOSEPH MURDOCH. P. vi, 55; 20 figs. Dubuque, Iowa, 1957 (Wm. C. Brown Co., $2.75).—The authors' purpose is to provide the basis for a minimum course in crystallography, and their actual success will be determined by use of the manual rather than by the opinions of reviewers. A number of shortcomings common in other books have been avoided, as in making accurate crystal drawings that actually correspond to the representative stereographic projections of the crystal classes (Table 8), also in certain classes (like 3 2/m, familiar as that of calcite) where there is some freedom in the choice of the *a*-axes, parallel or perpendicular to the 2-fold symmetry axes, this freedom and its consequences are explicitly noted

with good effect. The order of chapters may be summarized: 1-2. Introduction to crystal structure; measurement of angles. 3-4. Zones; crystal axes; axial ratios: Miller indices. 5. Stereographic projection. 6. Crystal classes and systems. 7-8. Crystal forms. 9. Calculations. 10. Use of determinative tables. Appendix. List of minerals in each crystal class. No alphabetical index is provided, but for such a short manual it hardly seems necessary.

It is good to find the use of International symmetry symbols in place of names for the 32 crystal classes. Possibly the names should have been included, although they are certainly not immediately important to the beginning student.

This manual looks like the clear, concise, and accurate work that has long been needed for elementary courses in mineralogical crystallography. It is well worth a classroom trial. Congratulations to the authors!

HORACE WINCHELL

Landslides in Clays, a translation by W. R. SCHRIEVER of *Recherches expérimentales sur les glissements spontanés des terrains argileux*: by ALEXANDRE COLLIN (Paris, 1846). Pp. xxxvi, 160. Toronto, 1956 (Univ. Toronto Press, $6.50).—This first appearance in English translation of a book published more than 100 years ago implies that there is something exarordinary about the work and its author. There is indeed.

Collin was an engineer in the Corps Royal des Ponts et Chaussées. While engaged in the construction of canals and reservoirs in east-central France he had the opportunity to study many failures of natural and artificial slopes. From observations and measurements made by himself and his colleagues he drew certain conclusions regarding the mechanism and causes of landslides in clayey strata. These conclusions not only differed from the opinions held by authorities of his time but also anticipated to a remarkable degree some of the important developments in the field of soil mechanics attained during the last thirty years.

One of the present-day leaders in this science, Dr. A. W. Skempton, has analyzed the significance of Collin's work in a memoir that accompanies the translation. Collin's attentions were directed toward rotational slips in stiff-fissured clays and in earth dams and embankments. He recognized that the surface of slip was not a pre-existing flaw but a product of the movement itself. By actual measurements, he determined that the slip surface was not plane, as generally supposed, but curved in the shape of a cycloid in vertical section. Collin did not speculate on why the slip surface should assume cycloidal shape. The whole matter of cycloidal slips in plastic deformation apparently did not receive further attention for sixty years and even now is the subject of active research.

Collin saw also that the cause of failure was inadequate shear strength, and by field observation and laboratory experiments on clays he demonstrated that the part of shear strength due to cohesion is strongly dependent upon water content and to some degree upon duration of stress. He realized that the equilibrium profile of progressively softening clay strata is approached more or less closely by natural hillsides and that an engineer needs to protect

steeper artificial cuts by adequate drainage and other remedial measures. In much of this Collin was a pioneer and his new views were accepted by many engineers. Interest in analytical mechanics soon turned, however, toward materials other than soils, and Collin's work was practically forgotten.

This book is not as easy to read as a modern technical paper, for Collin presents his observations on individual slides and argues the controversial points at great length. Much of the discussion refers to details in the many figures in the 21 plates. These were reduced and reproduced in half-tone in the present translation. Doubtless this procedure was the best that could be followed under the circumstances. Most of the resulting illustrations, however, though preserving the flavor of the original draughtmanship, now leave much to be desired in clarity.

The translation itself appears to be a splendid job done on difficult material. In this Mr. Schriever was assisted at various times by J. P. Carrière, by R. F. Legget (who started the project), and by D. H. MacDonald. Only one question comes to mind. In several places, as on p. 15, it would appear that the word "shale" rather than "schist" would better fit the context.

Collin's work may be commended to all those interested in the development of the earth sciences both as to the subject and as a record of an independent thinker in the act of creating new and for that time heretical ideas from direct observation.

DAVID J. VARNES

Reptiles; by ANGUS D'A. BELLAIRS. P. 195, 12 figs. London, 1957 (Hutchinson's University Library; New York, Rinehart and Co., $1.50).—This extremely concise and well balanced account of living and fossil reptiles stresses the larger features of classification and phylogeny, and the anatomy, habits, and physiology of living reptiles rather than taxonomic details. The bibliography includes references to more extensive standard texts and to recently published research. Crocodilians and the squamata are discussed in more detail than other orders, as they form our principal basis for interpreting extinct reptiles.

In spite of a few errors, such as Prostegidae for Protostegidae (p. 63) and reference to phytosaurs from the South African Triassic (a region where they do not occur) (p. 96), this volume should form a convenient reference for anyone seeking reliable basic information concerning reptiles.

JOSEPH T. GREGORY

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